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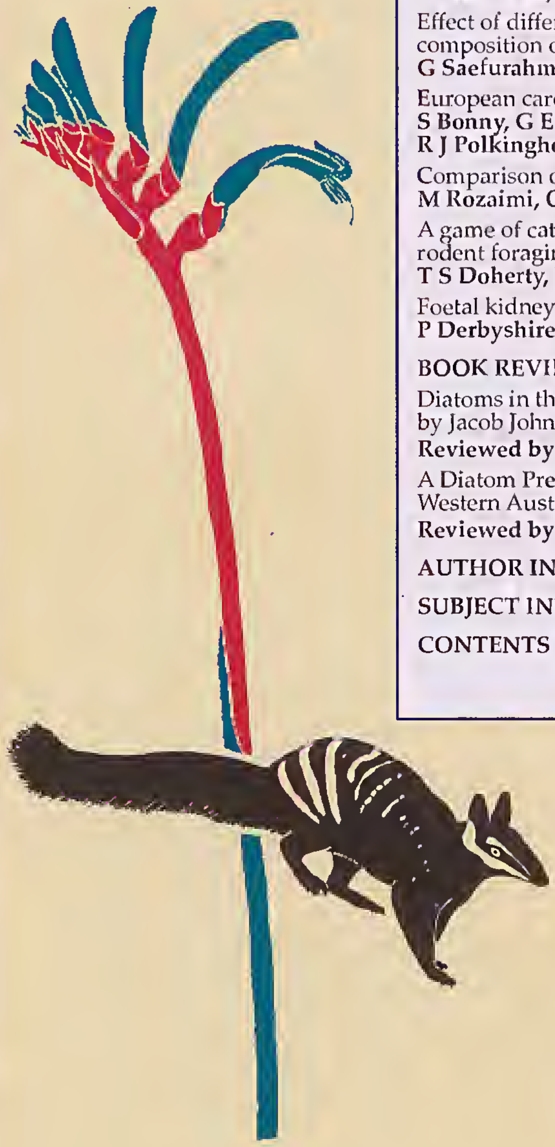

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Cover design: The four subjects symbolise the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Jan Taylor). The Gogo fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

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Avifauna of the Mulga–Eucalypt Line in Western Australia

MUSEUM VICTORIA
18 MAR 2014

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The Mulga–Eucalypt Line has long been recognised as a vegetational transition from *Acacia* spp. domination in the northeast to *Eucalyptus* spp. domination in the southwest. The avifauna of this transition zone was sampled over four seasons at four locations representing a north to south geographic gradient of ~170 km. Each location comprised one survey site dominated by acacias and a second dominated by eucalypts. A total of 81 avian species were recorded over the July 2011 to April 2012 sampling period with an average sample richness of 19 species per plot and a mean plot density of 1.05 birds/ha. Most species were classed as sedentary (39%), with the remainder as locally dispersive (21%), nomadic (25%) or migratory (15%). Ordination analysis indicated a latitudinal gradient of bird species from north to south along the first axis associated with gradually increasing rainfall. The second ordination axis revealed avian species differences dependent on the dominant vegetation. The third ordination axis displayed differences in bird species related to season, especially the spring and summer samples. The avifauna assemblage structure of northern locations was strongly influenced by the inclusion of irruptive, arid-zone nomadic species. Site richness comparisons between locations were not different, but eucalypt-dominated sites had more species than acacia-dominated sites. Site richness was greater during spring and summer. Density also was influenced by the influx of arid-zone nomadic species to the northern sites of the transition zone during spring and summer. Species diversity of the samples was influenced by vegetation type, but the measures of evenness and dominance were not affected by the factors of location, vegetation type or season. The Mulga–Eucalypt Line transition zone presently has considerable conservation value, but is under threat from pressures of agricultural and mining intrusions. Continued protection of native vegetation in the conservation reserves should be encouraged.

KEYWORDS: avifauna community, density, gradient analysis, Mulga–Eucalypt Line, seasonal variation, species richness, vegetation.

INTRODUCTION

The Mulga–Eucalypt Line is a zone of vegetation change running inland from the Western Australian coastal town of Geraldton southeastward through Menzies in the Goldfields (Beard 1990). The line separates the Eremaean Botanical Province to the north and the South-West Botanical Province to the south (Figure 1) and also separates the Southwestern and the Central Provinces of the Western Faunal Sub-Region (Kikkawa & Pearse 1969).

The predominant tree species of the arid regions to the northeast is mulga (*Acacia aneura*), associated with a number of other acacias (e.g. *A. pruinocarpa, A. linophylla, A. coriacea* and *A. acuminata*). The predominant tree species of the more mesic areas to the southwest are eucalypts (e.g. *Eucalyptus salmonophloia, E. loxophleba, E. salubris* and *E. transcontinentalis*) (Boland *et al.* 1984). The vegetation transition from acacia to eucalypt domination has been variously attributed to climatic variables (Beard 1990), predominately rainfall (Patrick 2001), although edaphic parameters play a role within the transition zone (Beard 1990). The Mulga–Eucalypt Line roughly lies between the 250–350 mm rainfall isohyets and separates the arid zone of the northeast with limited rainfall occurring in both summer and winter, from the more mesic Mediterranean climate of the southwest with wet winters and dry summers. Within the transition zone, mulga woodlands with trees 3–4 m in height occur on shallow, red-loam soils overlying hardpan (Beard 1990; Patrick 2001). Eucalypt woodlands in this region with trees to 10 m occur on deeper loam soils with the depth to the hardpan favouring different eucalypt species.

Birds of arid-zone mulga regions of Western Australia have been surveyed by Cody (1994), Recher & Davis (1997), Burbidge *et al.* (2000, 2010) and Bell *et al.* (2013). Serventy & Whittell (1962) noted that bird populations along the Mulga–Eucalypt Line were an admixture of birds of the more arid woodlands, scrublands and hummock grasslands to the north and east and those of the more mesic woodlands and forests to the south and west. A number of studies of the avifauna of *Eucalyptus*-dominated sites south of the Mulga–Eucalypt Line have been published (Ford 1971; Davies 1977; Arnold & Weeldenburg 1998; Recher & Davis 2002, 2010; Bell *et al.* 2007, 2010). Bell *et al.* (2007) showed that there was a gradient of avian assemblage change from northeast to southwest from surveys of exclusively eucalypt woodlands in the northern part of the South-West Botanical Province. A study specifically designed to determine if the avifauna changes across the Mulga–Eucalypt Line or if birds inhabiting *Acacia*-dominated habitats are different from those of adjacent *Eucalyptus*-dominated habitats in the transition zone has not been attempted. The objectives of this study were to: (i)

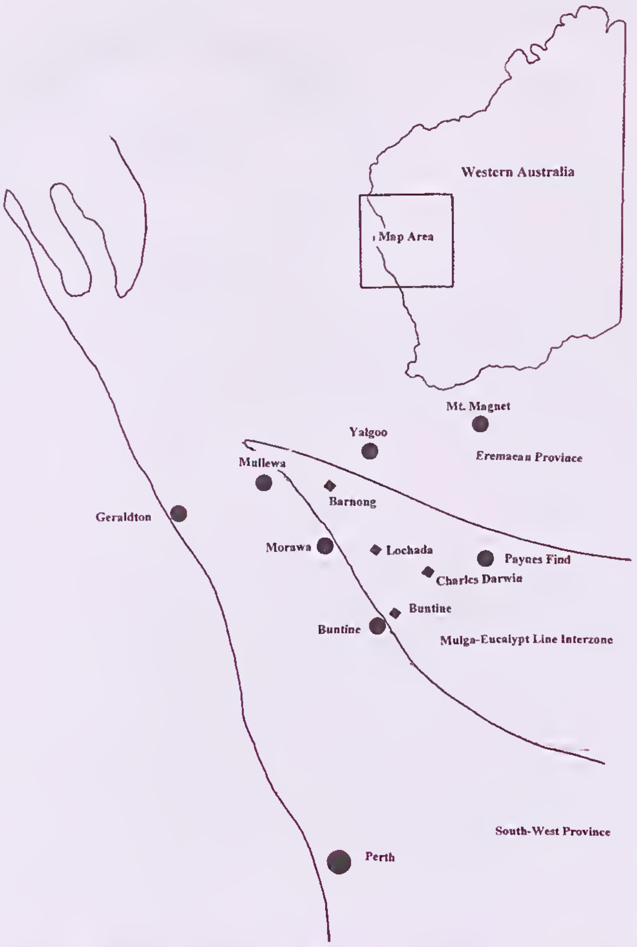

Figure 1 Study area map depicting northwestern region of the Mulga–Eucalypt Line vegetation transition zone between the Eremaean Botanical Province in the northeast and the South-West Botanical Province in the southwest with the local towns in black circles and the study sites in black diamonds.

document the avifauna of this vegetation zone; (ii) determine if a gradient in the avifauna occurs from north to south across this region; (iii) assess whether there are differences in bird assemblages from sites dominated by acacia versus nearby sites dominated by eucalypts; and (iv) determine possible seasonal differences in bird assemblages.

METHODS

Study sites

The avifauna of the Mulga–Eucalypt Line was sampled at four locations (Barnong Nature Reserve, Lochada Nature Reserve, Charles Darwin Reserve and Buntine Nature Reserve) (Figure 1). The four sampling locations also represented a north to south geographic gradient of ~170 km. Details of the geographic location of each study site and the dominant plant species are presented in Table 1. All sites are in native vegetation regions managed for conservation and have been unburned for many years. The Lochada sites are in the Karara and Lochada Important Bird Area (IBA) and the Charles Darwin sites are in the Mt Gibson and Charles Darwin IBA (Dutson *et al.* 2009). Mean annual rainfalls for the nearest Bureau of Meteorological Stations (www.bom.gov.au/climate) for each site were 261 mm for Barnong (Yalgoo), 291 mm for Lochada (Morawa), 282 mm for Charles Darwin (Paynes Find) and 342 mm for Buntine (Buntine).

Sampling procedures

Each of the four sampling locations included two avian survey sites, one in *Acacia*-dominated vegetation and a second in *Eucalyptus*-dominated vegetation. The survey site vegetation, however, was not completely exclusive, since the understory of the *Eucalyptus*-dominated sites had a number of shrubby acacias and the *Acacia*-dominated sampling locations had sporadic eucalypt trees. Each permanently marked survey site was a plot of 500 m radius (78.54 ha) centred in a region of representative vegetation and divided into four quadrants (0-90°, 90-180°, 180-270° and 270-360°). The first two authors shared the field observation and recording of data. Each quadrant was traversed during a half-hour period and all birds heard or sighted were identified, tallied and recorded. Two periods of sampling, one in the early morning and one in the late afternoon, were made for each quadrant in each vegetation type for each season. All four quadrants for a single site were surveyed consecutively. Sampling took place in mid-winter (3–14 July 2011), mid-spring (10–22 September 2011), mid-summer (30 December 2011 to 7 January 2012) and mid-autumn (10–18 April 2012). No samples were taken during rainy or excessively windy conditions. There were no major eucalypt-flowering episodes at any of the

Table 1 Mulga–Eucalypt Line sampling site information.

Location	Latitude	Longitude	Major species
Barnong acacia	28°25.65'S	116°07.86'E	*Acacia linophylla, Melaleuca uncinata*
Barnong eucalypt	28°25.40'S	116°08.52'E	*Eucalyptus loxophleba, E. oleosa*
Lochada acacia	29°12.04'S	116°30.89'E	*A. aneura, A. linophylla*
Lochada eucalypt	29°12.14'S	116°31.53'E	*E. salmonophloia, E. loxophleba*
Darwin acacia	29°35.14'S	116°57.57'E	*A. aneura, Callitris spp., Melaleuca spp.*
Darwin eucalypt	29°36.62'S	116°55.13'E	*E. salmonopholia, E. loxophleba*
Buntine acacia	29°58.02'S	116°35.29'E	*A. acuminata, Casuarina spp.*
Buntine eucalypt	29°58.80'S	116°34.74'E	*E. loxophleba*

sampling sites or seasons. All sites in a single location were sampled at one time, but the order of the locations was randomised in each season's surveys. Sampling was also randomised for vegetation type and then the particular sampling quadrant.

Avian nomenclature followed Christidis & Boles (2008). Movement status designations were determined from the works of Saunders & Ingham (1995), Johnstone & Storr (1998, 2004), Morcombe (2000), Simpson & Day (2004), Recher & Davis (2002, 2010) and Bell *et al.* (2007, 2010).

Statistical analyses

Relative density of each species in each sample was calculated by dividing the number of observations of that species by the total number of birds observed in the sample. In order to reveal patterns of overall avian community structure and patterns of individual bird species distributions, the matrix of relative density data was analysed by Detrended Correspondence Analysis (DCA) (Jongman *et al.* 1995). The matrix included only bird species that occurred in at least two samples.

Characteristics of the avian population of each site were also described in terms of site richness, density and species population heterogenity. Avifauna richness was determined as the total number of bird species recorded at each site during the 4 hours of sampling for each season. Site avifauna density (birds/ha) was the total number of observations of all birds for the two surveys (am and pm) divided by two and then by 78.54 (sample area site). Due to the major irruption of the population of budgerigars in the spring, counts continued only up to a maximum of 100 individuals within any one quadrant. As a result, bird densities during spring could have been underestimated. Three measures of site species heterogeneity were determined: Shannon indices of diversity ($H' = \Sigma p_i \log_{10} p_i$), evenness ($J' = H'/H'_{max}$) and the Simpson index of dominance ($D = \Sigma p_i^2$), where p_i equals the proportion for the ith species. These indices combine both species richness and the evenness of distribution of individuals within the sample (Peet 1974). The Shannon indices are biased toward species richness, while the Simpson index of dominance is biased toward the density of the most common species (Magurran 1988).

Relationships between geographic location, vegetation type and seasonal variation and the DCA site axis scores were explored by correlation analysis and where significant associations found, differences were tested by unpaired t-tests (Zar 1996). A two-way repeated measures ANOVA was used to test aspects of the avian assemblage structure, richness, density, species diversity, evenness and dominance (dependent variables) against independent variables geographic location, vegetation type and seasonal variation (Zar 1996). Where the ANOVA indicated significance Holm-Sidak post-hoc multiple comparison calculations were made to compare differences between groups. No significant interactions were found between the main factors in any ANOVA. While the original data were found to be not normally distributed, even after square-root transformation, all data met the equal-variance test. The results reported are based on square-root transformed data. All statistical testing was carried out using Sigma Stat® 3.5 (Systat Software Inc. 2006).

RESULTS

General avian community

A total of 81 species were recorded in the 2011–2012 samples of birds of the Mulga–Eucalypt Line region, including 30 non-passerines and 51 passerines (Appendices 1, 2). Species richness values for the individual sample locations were similar, ranging between site totals of 47 and 54 species. Species totals separated by vegetation type were also similar with 68 species recorded in *Acacia*-dominated sites and 66 species in *Eucalyptus*-dominated sites (Table 2). Of the species recorded, 39% were classed as sedentary, 21% as locally dispersive, 25% as nomadic and 15% as migratory. Red-capped robin and chestnut-rumped thornbill were the most frequently observed species, each occurring in 31 of the 32 separate samples. Other sedentary and/or locally-dispersive species occurring in more than 75% of samples included the Australian raven, Australian ringneck, grey shrike-thrush and inland thornbill.

Nomadic and/or migratory species appeared in the records of particular seasons. Among these highly mobile species, which were observed only in winter and spring, were the black-eared, pallid and Horsfield's bronze cuckoos, regent parrot and white-winged triller. Black and pied honeyeaters and the rufous songlark were only recorded in the spring samples. Species restricted to only the spring and summer samples included budgerigar, cockatiel, red-backed kingfisher, black-faced cuckoo-shrike and white-fronted honeyeater. Rainbow bee-eater, brown songlark and crimson chat were recorded only in the summer and zebra finch was recorded only in summer and autumn.

Table 2 Species richness and movement type percentages of the avifauna of the Mulga–Eucalypt Line including all samples, samples of acacia sites alone and eucalypt sites alone and the separate seasons alone.

	All	Acacia	Eucalypt	Winter	Spring	Summer	Autumn
Richness	81	68	66	49	57	53	38
Movement Type							
Sedentary	39%	38%	39%	49%	37%	43%	47%
Locally Dispersive	21%	22%	21%	20%	18%	27%	26%
Nomadic	26%	25%	24%	17%	28%	21%	16%
Migratory	14%	15%	15%	14%	17%	9%	11%

Avian assemblage patterns

The DCA ordination procedure utilised a matrix of 62 avian species and 32 samples, after singletons were removed from the complete set of relative densities. The first DCA axis explained 48% of the sample variance and separated the samples on a geographic gradient (Figure 2). The highest first axis sample scores were from Barnong. Lochada samples tended to be grouped in the central section of the first axis and Darwin and Buntine samples were located on the low-score end of the first axis. Correlation analysis revealed a significant ($r_{30} = 0.61$, $p \leq 0.05$) relationship between sample latitude and the DCA first axis score.

The second DCA axis, which explained another 22% of the sample variance, separated samples from the acacia sites at the higher score end of DCA axis 2 from the eucalypt site scores at the lower end (Figures 2, 3). An unpaired t-test of the second axis DCA sample scores between the acacia sites and the eucalypt sites indicated that the bird assemblages were significantly different ($t_{30} = 4.59$, $p \leq 0.001$) between vegetation types.

The third DCA axis explained a further 15% of the sample variance and separated the spring samples at the upper end of axis 3 from the summer samples at the lower end of axis 3 (Figure 3). One-way analysis of variance for axis 3 sample scores indicated that season also had a significant ($F_{3,28} = 3.95$, $p \leq 0.05$) effect on the bird assemblages of the region.

Particularly diagnostic species (those with very high or very low DCA species scores) influenced the position of the samples along the geographic gradient of the first DCA axis (Appendices 1, 2). Northern species included black and pied honeyeaters, budgerigar, cockatiel, zebra finch and little button-quail. All these arid-zone birds were classed as nomadic or migratory birds. Species with low DCA axis 1 values were in the more southerly and mesic end of the geographic gradient and included the black-faced cuckoo-shrike, black-faced woodswallow, grey fantail, yellow-rumped thornbill and red wattlebird.

Avian species strongly influencing the second DCA sample axis and related to vegetation differences included the singing honeyeater, black-faced cuckoo-shrike, rufous songlark, crested pigeon and mulga parrot which had higher scores and were associated with acacia sites. Species with lower scores that were associated primarily with samples from eucalypt sites included the rufous treecreeper, red-backed kingfisher, weebill, regent parrot, striated pardalote and Major Mitchell's cockatoo.

Budgerigar, cockatiel, western corella and crimson chat, species recorded in greatest numbers in spring, influenced the samples on upper end of DCA sample axis 3. Species with low DCA species axis 3 scores were rainbow bee-eater, Nankeen kestrel and Australian magpie, which were recorded only in summer.

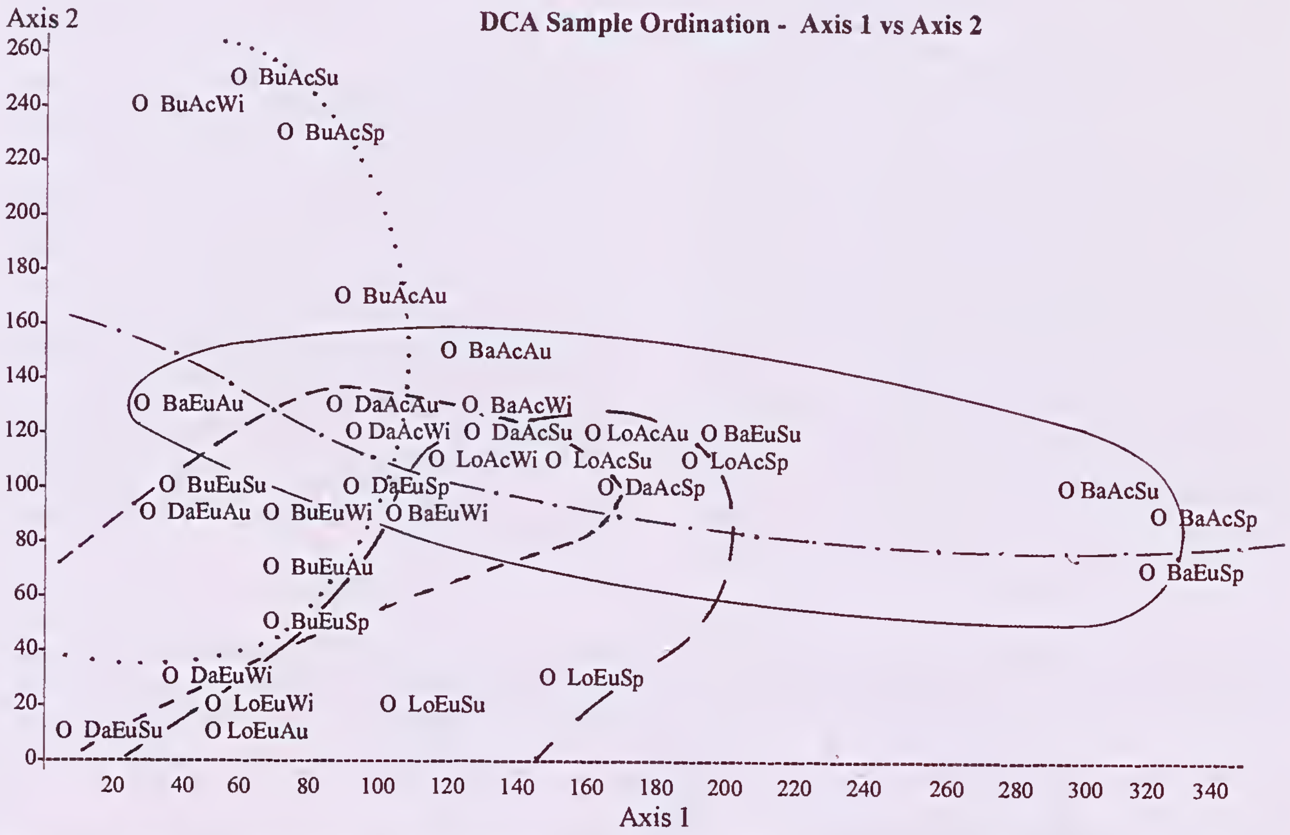

Figure 2 Detrended Correspondence Analysis sample plot for axis 1 values against axis 2 values. The first two letters of the name of the site, the vegetation type and the sampling season designate each sample. On axis 1, values related to the samples from the same location are enclosed by lines of different types: Barnong ———; Lochada — — —; Charles Darwin – – –; Buntine ····. On axis 2, values related to the two vegetation types are separated by the dash-dot-dash line.

Avian community characteristics

Overall, sample richness averaged 19.5±0.8 species per sample (Table 3). However, there was considerable variation between samples. The lowest number of species in a single sample was 14 recorded during winter at the Barnong acacia site. The highest number of species recorded was 28 at the Barnong eucalypt site during summer. Although there were no statistical differences in sample richness between the four locations, the mean number of bird species in eucalypt sites was significantly greater than in acacia sites ($F_{1,3}$ = 30.75, p ≤0.01). The repeated measures ANOVA showed richness of samples in spring and summer to be significantly greater than the samples of winter and autumn ($F_{3,9}$ = 6.90, p ≤0.01).

Bird density in the Mulga–Eucalypt Line during 2011–2012 was generally low at a mean of 1.05 birds/ha, but

Table 3 Richness (no. of species), density (birds/ha), species diversity (H'), evenness (J') and dominance (D) of samples of the Mulga–Eucalypt Line. Values with same superscript within the same factor are not different at p ≤0.05.

	Richness	Density	Diversity	Evenness	Dominance
Overall	19.47 ± 0.76	1.05 ± 0.19	1.03 ± 0.02	0.80 ± 0.02	0.15 ± 0.02
Location					
Barnong	18.88 ± 2.00 ^{a}	1.79 ± 0.69 ^{a}	0.89 ± 0.10 ^{a}	0.71 ± 0.08 ^{a}	0.23 ± 0.09 ^{a}
Lochada	20.50 ± 1.57 ^{a}	0.97 ± 0.08 ^{a}	1.08 ± 0.04 ^{a}	0.83 ± 0.02 ^{a}	0.11 ± 0.01 ^{a}
Darwin	19.50 ± 1.50 ^{a}	0.87 ± 0.19 ^{a}	1.04 ± 0.03 ^{a}	0.81 ± 0.02 ^{a}	0.11 ± 0.02 ^{a}
Buntine	19.00 ± 1.18 ^{a}	0.58 ± 0.06 ^{a}	1.10 ± 0.07 ^{a}	0.87 ± 0.04 ^{a}	0.16 ± 0.04 ^{a}
Vegetation					
Acacia	17.56 ± 1.09 ^{a}	0.82 ± 0.20 ^{a}	0.99 ± 0.04 ^{a}	0.80 ± 0.03 ^{a}	0.15 ± 0.03 ^{a}
Eucalyptus	21.38 ± 1.07 ^{b}	1.29 ± 0.30 ^{b}	1.07 ± 0.06 ^{b}	0.81 ± 0.04 ^{a}	0.16 ± 0.04 ^{a}
Season					
Winter	16.88 ± 1.03 ^{ac}	0.61 ± 0.09 ^{a}	1.00 ± 0.03 ^{a}	0.82 ± 0.01 ^{a}	0.15 ± 0.01 ^{a}
Spring	22.50 ± 1.29 ^{b}	1.91 ± 0.70 ^{a}	1.00 ± 0.13 ^{a}	0.74 ± 0.08 ^{a}	0.28 ± 0.09 ^{a}
Summer	21.88 ± 1.42 ^{bc}	0.93 ± 0.09 ^{a}	1.11 ± 0.04 ^{a}	0.83 ± 0.02 ^{a}	0.11 ± 0.02 ^{a}
Autumn	16.63 ± 1.31 ^{a}	0.77 ± 0.17 ^{a}	1.00 ± 0.04 ^{a}	0.82 ± 0.02 ^{a}	0.07 ± 0.01 ^{a}

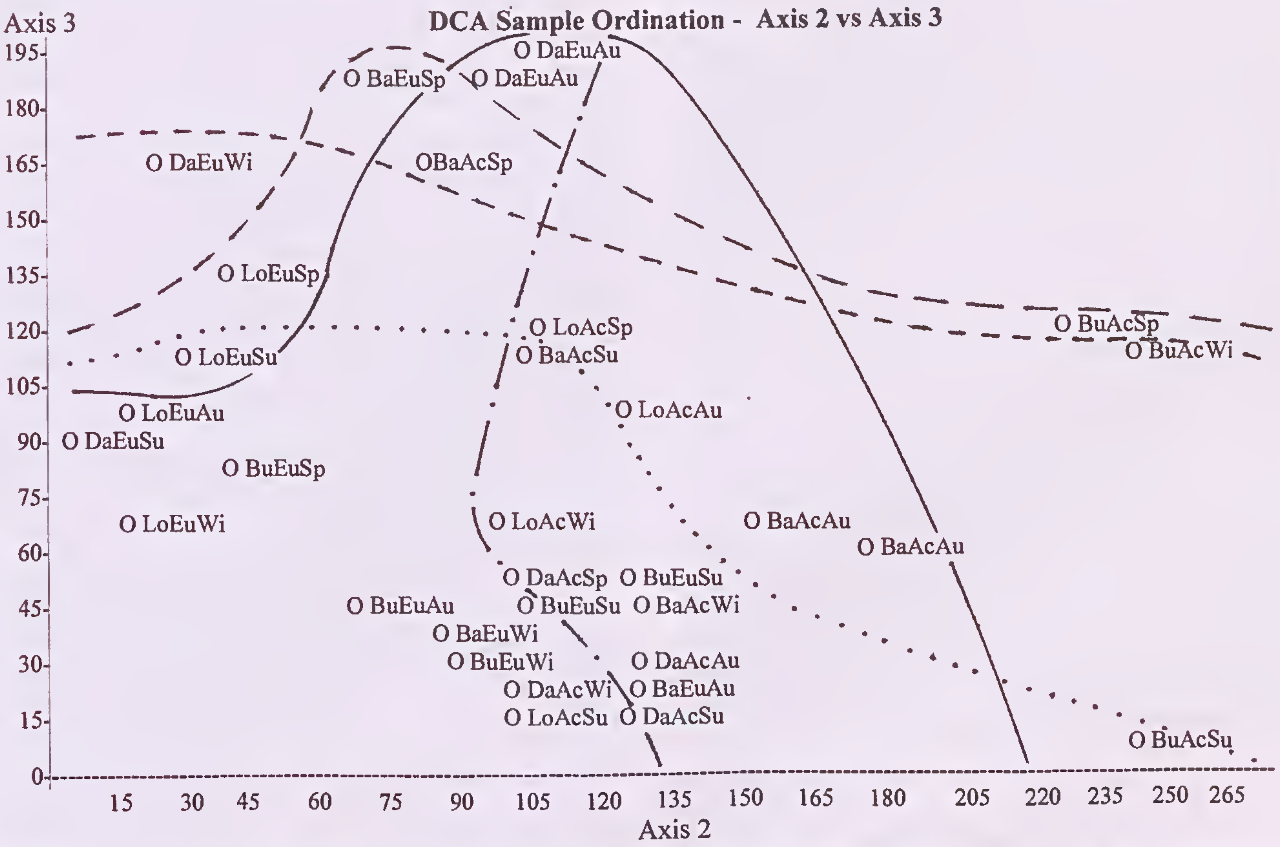

Figure 3 Detrended Correspondence Analysis sample plot for axis 2 values against axis 3 values. The first two letters of the name of the site, the vegetation type and the sampling season designate each sample. On axis 2, values related to the two vegetation types are separated by dash-dot-dash line as in Figure 2. On axis 3, values related to the samples from the same seasonal samples are enclosed by lines of different types: Autumn ———; Spring — — —; Winter- - -; Summer ····.

highly variable (Table 3). Only vegetation type had a significant ($F_{1,3}$ = 16.06, $p \leq 0.05$) influence on the mean density of birds in the study samples, with eucalypt sites having greater density compared to acacia sites.

The Shannon measure of species diversity (H') averaged 1.03±0.02 overall (Table 3). As with the measures of bird density, only samples varying by vegetation type were significantly ($F_{1,3}$ = 10.34, $p \leq 0.05$) different with eucalypt-dominated sites being more diverse than acacia-dominated sites. The statistical comparisons of the evenness (J') and dominance (D) showed no difference due to location, vegetation type or season of samples. Although there were no statistical differences in sample richness between the four locations, the repeated measures ANOVA (square-root transferred) showed the mean number of bird species in eucalypt sites was significantly greater than in acacia sites ($F_{1,3}$ = 30.75, $p \leq 0.01$); furthermore, the richness of samples in spring and summer to be significantly greater than the samples of winter and autumn ($F_{3,9}$ = 6.90, $p \leq 0.01$).

DISCUSSION

During the sampling period of July 2011 to April 2012, the avifauna of the Mulga–Eucalypt Line varied in relation to a north to south geographic gradient mainly in the pool of available sedentary and locally dispersive species, but also as a result of the presence of a number of nomadic and migratory birds in northern sites. There was a secondary influence of vegetation type, with some birds associated with *Acacia*-dominated sites and others associated with *Eucalyptus*-dominated sites. Seasonal variation in the avifauna of sites appeared small, as the majority of species were either sedentary or locally dispersive species. Minor seasonal differences were due to the influx of nomadic and migratory species during spring and summer.

Geographic pattern

The geographic variation in avian assemblage noted in the Mulga–Eucalypt Line has been recorded for other Western Australian regions. A biogeographic gradient in avian population structure associated primarily with rainfall was documented along the northern portion of the South-West Botanical Province in vegetation dominated by eucalypt species (Bell *et al.* 2007). Also, a gradual, broad-scale change in avian community structure due to climatic factors was the primary influence in a study of biogeographic patterns in birds of the Carnarvon Basin, well to the north of the present study region (Burbidge *et al.* 2000). Birds in the southern sites of the study area were primarily sedentary and locally dispersive species, while the more northern sites included a number of arid-zone nomadic species.

Influence of vegetation type

The samples of the bird assemblages of the Mulga–Eucalypt Line also showed differences in composition between the *Acacia*-dominated sites and nearby *Eucalyptus*-dominated sites. The singing honeyeater, black-faced cuckoo-shrike, rufous songlark, crested pigeon and mulga parrot were species strongly associated with *Acacia*-dominated sites of the region. All these species have been previously associated predominantly with *Acacia* spp. (although not strictly *Acacia aneura*-dominated vegetation sites) (Cody 1994; Burbidge 2010; Bell *et al.* 2013). Species more likely to be associated with *Eucalyptus*-dominated woodlands included the rufous treecreeper, weebill, red-backed kingfisher, tawny frogmouth, Major Mitchell's cockatoo, red-tailed black cockatoo, regent parrot, brown goshawk and brown falcon. The differential use of particular tree species by birds recorded in our study has been observed in a range of other studies (Hartley 1953; Franzreb 1978; Noske 1979; Ford *et al.* 1986; Holmes & Robinson 1981). A number of reasons have been suggested for the preference of particular tree species by birds. The abundance, biomass and availability of insect resources and the relative abundance of particular tree species in a region may have relevance to insectivorous birds choosing certain tree species (Abbott & Van Heurck 1985). *Acacia* and *Eucalyptus* support entirely different psyllid subfamilies (New 1988), but data from studies from woodlands and forests in Western Australia indicate that there is high overlap among the insects eaten by bird species (Calver & Wooller 1981; Wooller & Calver 1981; Tullis *et al.* 1982; Abbott & Van Heurck 1985; Carver *et al.* 1991; Majer *et al.* 1997). Leaf morphological and nutrient differences in leaves between tree species may also be relevant in facilitating the search for insects among foliage elements (Jackson 1979; Braithwaite *et al.* 1989; Recher *et al.* 1996; Watson 2011). Large trees for nesting and perching may be related to the presence of particular raptors (Storr 1984; Aumann 2001). Nest hollows for some species of parrots could also influence a preference for eucalypt-dominated sites.

Seasonal differences

Minor differences in avifauna assemblage of the Mulga–Eucalypt Line were also found between the four seasonal samples of the July 2011 to March 2012 sampling period. As 70% of the bird species recorded were classed either as sedentary of locally dispersive, seasonal differences might be expected to be small. However, a wide number of arid zone birds in Australia are known to be highly responsive to changes in available food and water resources (Davies 1984; Pavey & Nano 2009). Bell *et al.* (2007) found that the influx of nomadic honeyeaters during episodes of eucalypt flowering strongly influenced the avian associations of eucalypt sites to the south of the Mulga–Eucalypt Line. In the current study, black and pied honeyeaters, two opportunistic nectarivores, occurred in the northern sampling sites during spring, but a general lack of flowering episodes in eucalypt species during the sampling period could have limited any variation in avian assemblage structure due to season. Three species of migratory cuckoos, Horsfield's bronze cuckoo, pallid cuckoo and black-eared cuckoo, were recorded in the Mulga–Eucalypt Line samples, but none were numerous. Other Mulga–Eucalypt Line species listed as migratory, including the striated pardalote, white-winged triller, rufous songlark, tree martin and grey fantail, were also recorded occasionally during the 2011–2012 sampling period, but were never numerous. Nix (1976) characterised a number of Western Australian species as migratory. Keast (1968) also reported information related to the seasonal migratory movements of a range species, including a number of honeyeaters. It is apparent, however, that further analysis of the movement patterns of arid-zone birds and the classification of the species as either migratory or nomadic is needed. The lack of tagging and recapture studies of terrestrial birds of Australia is a major impediment in the determination of the potential influence of migration on the presence of species in arid-zone samples (Griffioen & Clarke 2002).

Bird richness, density and heterogeneity

Mean species richness within the Mulga–Eucalypt Line was not affected by location, although richness of eucalyptus sites was greater than acacia sites and sample richness in spring and summer was enhanced over samples from autumn and winter. Generally, habitats that are more productive, of greater maturity and/or have greater habitat heterogenity are richer in animal assemblages (Ricklefs & Schluter 1993). However, this does not seem the case for Western Australian bird assemblages, as samples from a very wide range of sites all have similar site richness values. The mean richness of samples of the avifauna of the Mulga–Eucalypt Line at 19.5 species was similar to those recorded for avifauna of the Pilbara much further to the north, as measured by Burbidge *et al.* (2010), which averaged 19.1 species. In the Doolgunna and Mooloogool Rangelands of the northeastern Gascoyne, also to the north of the present samples, species richness averaged 21.7 species per sample (Bell *et al.* 2013). Managed eucalypt forest sites, well to the southwest of the Mulga–Eucalypt Line, typically contain 10–33 bird species per site (Williams *et* al. 2001; Abbott *et al.* 2003). *Eucalyptus*-dominated sites in the northern regions of the South-West Botanical Province, also south of the present study, averaged 27.3 species per sample in the study by Bell *et al.* (2007). Cousin & Phillips (2008) hypothesised that scarcity of food resources results in a species richness threshold beyond which there is insufficient resources to support additional species as habitat complexity increases. Low species richness of Western Australian regions relative to other Australian regions has also been associated with reduced numbers of nectar-feeding species and fewer litter-, trunk- and bark-gleaning species (Nichols & Muir 1989; Woinarski *et al.* 1997). The lack of eucalypt flowering episodes during our sampling period might have further influenced possible richness differences due to season by reducing the number of expected nectar-feeding nomadic honeyeaters. Careful documentation of vegetation structural complexity could provide more conclusive evidence to compare species richness values between north to south gradients in Western Australia and to compare the species richness of Western Australia sites to comparably complex habitats of eastern Australia.

Slight changes in the avifauna of spring and summer in the samples of the Mulga–Eucalypt Line were mainly due to the inclusion of a few nomadic and migratory species to the sedentary and locally dispersive species present in all seasons. Reduced impetus for migration due to the general lack of a large seasonal variation in resource availability has previously been highlighted for the restricted richness of Western Australian avifaunal assemblages (Nichols & Muir 1989) and may be an influence affecting the richness of samples in our study.

Bird density of sites of the Mulga–Eucalypt Line averaged 1.05±1.07 birds/ha. However, during spring the sample in the *Eucalyptus*-dominated site of the Barnong Nature Reserve rose to 5.87 birds/ha due primarily to the irruption in populations of budgerigars and cockatiels. The density of birds in sites of the Mulga–Eucalypt Line was generally much lower than in more mesic Australian habitats. Density of birds in tropical eucalypt savanna woodlands of the Northern Territory is quite high at 9.4 birds/ha (Woinarski & Tidemann 1991). Density of birds in southwestern Western Australian jarrah forest is also relatively high at 5.2 birds/ha (Nichols & Muir 1989). In mallee-boombush (*Melaleuca uncinata*) habitats of northeastern Victoria, bird density is ~3.0 birds/ha (Gilmore 1985). Bird density in relation to habitat resource availability obviously requires further research.

Species diversity (H') in the Mulga–Eucalypt Line averaged 1.03. Evenness (J') averaged 0.80 and dominance (D) averaged 0.15. Species diversity values of the winter sample *Eucalyptus*-dominated sites of Bell *et al.* (2007) in the more mesic region to the south of the Mulga–Eucalypt Line averaged slightly higher at 1.12, possibly due to the more even distribution of the densities of individuals among the species. The measures of heterogeneity in the Mulga–Eucalypt Line, however, were quite variable, probably due to the influx of a number of irruptive species of the arid interior during spring and summer. Our findings generally concur with those of Keast (1985), who stated that eucalypt communities throughout Australia vary little in total avian species diversity, although the causes are not known.

All sites utilised in this study were within protected conservation reserves, although much of the Mulga–Eucalypt Line region is increasingly being affected by mining, wheat farming and sheep-grazing activities. Continued protection of the reserves by the Western Australia Department of Parks and Wildlife and independent conservation organisations, such as Bush Heritage Australia, is essential for the maintenance and conservation of the avifauna of this important vegetation transition zone between the arid zone of central Australia and the woodlands and forests of the southwest Western Australia.

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Appendix 1 *Acacia* plot species composition, DCA site and species scores, total number of observations, species movement type and percentage of observations for each site, vegetation type and season for all acacia sites during the 2011–2012 survey period.

Site			Barnong	Lochada	Darwin	Buntine	Barnong	Lochada	Darwin	Buntine
Vegetation			Acacia							
Season			Winter				Spring			
DCA Axis 1 Sample Score			114	117	103	24	324	185	160	69
DCA Axis 2 Sample Score			123	97	101	237	85	105	95	227
DCA Axis 3 Sample Score			40	60	26	103	164	119	56	118
Total Number of Observations			69	125	54	61	570	147	107	74
Common name	Scientific name	Movement type								
Australian hobby	*Falco longipennis*	Loc.Disp.	-	-	-	-	-	-	-	-
Australian magpie	*Cracticus tibicen*	Loc.Disp.	-	-	-	-	-	-	-	-
Australian owlet-nightjar	*Aegotheles cristatus*	Sedentary	-	-	-	-	-	-	-	-
Australian raven	*Corvus coronoides*	Sedentary	1.45%	3.10%	-	1.64%	0.18%	2.70%	-	1.64%
Australian ringneck	*Barnardius zonarius*	Sedentary	-	6.20%	9.26%	3.28%	-	0.68%	1.87%	-
Black honeyeater	*Certhionyx niger*	Nomadic	-	-	-	-	2.98%	-	-	-
Black-eared cuckoo	*Chalcites osculaus*	Migratory	-	-	1.85%	-	-	-	-	3.28%
Black-faced cuckoo-shrike	*Coracina novaehollandiae*	Migratory	-	-	-	14.75%	-	-	-	-
Black-faced woodswallow	*Artamus cinereus*	Nomadic	-	-	-	-	-	-	-	-
Black-shouldered kite	*Elanus axillaris*	Loc.Disp.	-	-	-	-	-	-	-	-
Bourke's parrot	*Neopsephotus bourkii*	Nomadic	-	-	-	-	-	-	-	-
Brown falcon	*Falco berigora*	Sedentary	-	-	-	-	-	-	-	-
Brown goshawk	*Accipter fasciatus*	Loc.Disp.	-	-	-	-	-	-	0.93%	-
Brown songlark	*Cincloramphus cruralis*	Nomadic	-	-	-	-	-	3.38%	-	-
Budgerigar	*Melopsittacus undulatus*	Nomadic	-	-	-	-	76.49%	8.78%	-	-
Chestnut-rumped thornbill	*Acanthiza uropygialis*	Loc.Disp.	4.35%	9.30%	24.07%	4.92%	0.18%	6.08%	19.63%	4.92%
Cockatiel	*Nymphicus hollandicus*	Migratory	-	-	-	-	0.18%	-	3.74%	-
Collared sparrowhawk	*Accipiter cirrhocephalus*	Sedentary	-	-	-	-	-	-	-	-
Common bronzewing	*Phaps chalcoptera*	Loc.Disp.	-	-	1.85%	-	-	-	-	-
Crested bellbird	*Oreoica gutturalis*	Sedentary	4.35%	1.55%	-	-	0.70%	0.68%	6.54%	6.56%
Crested pigeon	*Ocyphaps lophotes*	Sedentary	-	-	-	3.28%	-	-	-	3.28%
Crimson chat	*Ephthianura tricolor*	Nomadic	-	-	-	-	-	11.49%	-	-
Diamond dove	*Geopelia cuneata*	Nomadic	-	-	-	-	-	-	-	-
Emu	*Dromaius novaehollandiae*	Loc.Disp.	-	-	-	-	-	-	-	-
Galah	*Eolophus roseicapillus*	Sedentary	-	-	1.85%	42.62%	0.53%	8.11%	-	44.26%
Grey butcherbird	*Cracticus torquatus*	Sedentary	-	-	-	-	-	-	-	-
Grey currawong	*Strepera versicolor*	Sedentary	-	2.33%	-	-	-	-	-	-
Grey fantail	*Rhipidura albiscapa*	Migratory	-	-	1.85%	1.64%	-	-	0.93%	-
Grey shrike-thrush	*Colluricincla harmonica*	Sedentary	2.90%	2.33%	-	3.28%	0.53%	0.68%	1.87%	3.28%
Horsfield's bronze-cuckoo	*Chalcites basalis*	Migratory	-	-	1.85%	-	0.53%	-	0.93%	-
Inland thornbill	*Acanthiza apicalis*	Loc.Disp.	24.64%	9.30%	11.11%	3.28%	0.88%	-	-	-
Little button-quail	*Turnix velox*	Sedentary	-	-	-	-	0.88%	1.35%	-	1.64%
Little crow	*Corvus bennetti*	Sedentary	-	-	-	-	-	6.08%	-	-
Major Mitchell's cockatoo	*Cacatua leadbeateri*	Sedentary	-	-	-	-	-	0.68%	-	-
Malleefowl	*Leipoa ocellata*	Sedentary	-	-	-	1.64%	-	-	-	-
Mistletoe bird	*Dicaeum hirundinaceum*	Nomadic	-	-	-	-	-	-	0.93%	-
Mulga parrot	*Psephotus varius*	Sedentary	-	3.10%	3.70%	-	-	-	2.80%	-
Nankeen kestrel	*Falco cenchroides*	Sedentary	-	-	-	-	-	-	-	-
Pallid cuckoo	*Cacomantis pallidus*	Migratory	-	-	-	-	-	0.68%	-	-
Pied butcherbird	*Cracticus nigrogularis*	Sedentary	-	1.55%	-	-	-	0.68%	-	-
Pied honeyeater	*Certhionyx variegatus*	Nomadic	-	-	-	-	7.72%	8.11%	3.74%	-
Rainbow bee-eater	*Merops ornatus*	Migratory	-	-	-	-	-	-	-	-
Red-capped robin	*Petroica goodenovii*	Loc.Disp.	20.29%	24.03%	25.93%	1.64%	2.46%	18.24%	14.95%	3.28%
Red-tailed black-cockatoo	*Calyptorhynchus banksii*	Nomadic	-	1.55%	-	-	-	0.68%	1.87%	-
Redthroat	*Pyrrholaemus brunneus*	Sedentary	5.80%	6.98%	9.26%	1.64%	0.88%	1.35%	0.93%	1.64%
Rufous songlark	*Cincloramphus mathewsi*	Migratory	-	-	-	-	-	0.68%	-	1.64%
Rufous whistler	*Pachycephala rufiventris*	Loc.Disp.	-	0.78%	-	-	0.53%	0.68%	8.41%	1.64%
Singing honeyeater	*Lichenostomus virescens*	Nomadic	4.35%	1.55%	-	9.84%	1.40%	1.35%	0.93%	16.39%
Southern boobook	*Ninox novaeseelandiae*	Sedentary	-	-	-	1.64%	-	-	-	-
Southern whiteface	*Aphelocephala leucopsis*	Sedentary	1.45%	3.10%	-	-	-	6.76%	-	3.28%
Spiny-cheeked honeyeater	*Acanthagenys rufogularis*	Nomadic	1.45%	-	-	-	0.53%	4.05%	11.21%	-
Splendid fairy wren	*Malurus splendens*	Loc.Disp.	14.49%	8.53%	5.56%	-	-	3.38%	3.74%	4.92%
Striated pardalote	*Pardalotus striatus*	Migratory	-	6.20%	-	-	-	-	-	-
Variagated fairy-wren	*Malurus lamberti*	Sedentary	-	-	-	-	1.40%	-	-	-
Wedge-tailed eagle	*Aquila audax*	Sedentary	-	-	-	-	-	-	-	-
Weebill	*Smicrornis brevirostris*	Sedentary	-	-	1.85%	-	-	-	-	-
Welcome Swallow	*Hirundo neoxena*	Nomadic	-	-	-	-	-	0.68%	-	-
Western Corella	*Cacatua pastinator*	Nomadic	-	-	-	-	-	-	-	1.64%
Western Yellow Robin	*Eopsaltria griseogularis*	Loc.Disp.	-	-	-	-	-	-	-	-
Whistling Kite	*Haliastur sphenurus*	Nomadic	-	-	-	-	-	-	0.93%	-
White-browed Babbler	*Pomatostomus superciliosus*	Sedentary	7.25%	-	-	4.92%	0.53%	-	-	18.03%
White-eared Honeyeater	*Lichenostomus leucotis*	Loc.Disp.	-	-	-	-	-	-	1.87%	-
White-fronted Honeyeater	*Purnella albifrons*	Nomadic	-	-	-	-	-	-	1.87%	-
White-winged Triller	*Lalage sueurii*	Migratory	-	5.43%	-	-	0.53%	0.68%	9.35%	-
Willie Wagtail	*Rhipidura leucophrys*	Loc.Disp.	1.45%	-	-	-	-	-	-	-
Yellow-rumped Thornbill	*Acanthiza chrysorrhoa*	Sedentary	-	-	-	-	-	1.35%	-	-
Yellow-throated Miner	*Manorina flavigula*	Loc.Disp.	5.80%	-	-	-	-	-	-	-
Zebra Finch	*Taeniopygia guttata*	Nomadic	-	-	-	-	-	-	-	-

Barnong	Lochada	Darwin	Buntine	Barnong	Lochada	Darwin	Buntine			
Acacia										
Summer				Autumn						
295	**140**	**109**	**61**	**119**	**131**	87	84			
100	**97**	**118**	**247**	**147**	**118**	**129**	**168**			
114	**10**	**16**	**0**	**66**	**94**	**28**	**60**	DCA Species Scores		
163	**166**	**115**	**100**	**46**	**94**	**96**	**67**	Axis 1	Axis 2	Axis 3
-	-	-	1.00%	-	-	-	-	-	-	-
-	4.82%	-	-	-	-	-	-	146	60	-346
-	-	0.87%	-	-	-	-	-	-	-	-
-	0.60%	2.61%	1.00%	-	1.06%	1.04%	5.97%	53	58	50
-	11.45%	4.35%	2.00%	-	4.26%	4.17%	5.97%	95	9	127
-	-	-	-	-	-	-	-	367	99	134
-	-	-	-	-	-	-	-	-11	-39	93
-	-	0.87%	1.00%	-	-	-	-	-132	329	-82
-	-	-	1.00%	-	-	-	-	-131	277	-167
-	-	-	1.00%	-	-	-	-	-	-	-
-	-	-	-	4.35%	-	-	-	29	251	172
-	3.01%	-	-	-	-	-	-	21	-26	-176
-	1.20%	-	-	-	-	-	-	37	-52	176
-	-	-	-	-	-	-	-	-	-	-
65.84%	-	-	-	-	-	-	-	352	70	187
1.24%	22.29%	23.48%	8.00%	28.26%	18.09%	35.42%	10.45%	51	100	14
9.32%	-	1.74%	-	-	-	-	-	293	-14	211
-	0.60%	-	-	-	-	-	-	92	-18	-253
-	1.81%	-	-	-	2.13%	-	2.99%	35	82	-63
0.62%	-	10.43%	-	-	-	-	-	176	122	45
-	1.81%	0.87%	-	-	-	-	5.97%	-7	298	46
-	-	-	-	-	-	-	-	286	79	216
0.62%	-	-	-	-	-	-	-	-	-	-
-	-	1.74%	-	-	-	-	-	182	54	86
-	-	-	4.00%	-	12.77%	2.08%	13.43%	55	243	241
-	-	-	-	2.17%	-	2.08%	-	-54	105	-47
-	3.01%	-	-	-	-	-	-	131	40	-117
-	-	-	-	-	-	3.13%	1.49%	-94	39	-155
1.86%	0.60%	0.87%	5.00%	-	-	1.04%	2.99%	151	166	131
-	-	-	-	-	-	-	-	264	47	-58
3.11%	2.41%	6.09%	4.00%	-	3.19%	-	4.48%	70	68	-8
4.97%	-	-	2.00%	-	-	-	-	304	234	17
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	27	-108	-36
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-
-	-	-	21.00%	-	-	8.33%	5.97%	38	293	-88
-	1.20%	0.87%	-	-	-	-	-	45	31	-183
-	-	-	-	-	-	-	-	253	-56	230
-	-	-	-	-	4.26%	-	-	81	-55	222
-	-	-	-	-	-	-	-	328	114	153
-	-	8.70%	2.00%	-	-	-	-	-9	230	-270
1.24%	5.42%	11.30%	3.00%	4.35%	6.38%	7.29%	7.46%	138	85	41
-	-	-	-	-	-	-	-	154	-59	231
9.32%	2.41%	4.35%	3.00%	4.35%	-	2.08%	7.46%	220	171	-20
-	-	-	-	-	-	-	-	182	320	214
1.86%	2.41%	5.22%	-	-	-	2.08%	2.99%	208	98	-4
1.24%	-	-	30.00%	-	-	1.04%	1.49%	23	367	16
-	-	-	-	-	-	-	-	-	-	-
-	-	7.85%	-	19.57%	13.83%	8.33%	-	131	111	138
6.83%	0.60%	-	1.00%	-	10.64%	3.13%	-	238	54	51
11.18%	12.65%	7.85%	4.00%	21.74%	15.96%	14.58%	8.96%	188	199	90
-	-	-	-	-	-	-	-	-74	16	198
-	-	-	-	-	-	-	-	-	-	-
0.62%	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-20	-66	131
-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	76	202	264
-	-	-	-	-	-	-	1.49%	-	-	-
-	-	-	2.00%	-	-	-	-	47	189	-44
-	-	-	-	6.52%	-	-	7.46%	-4	264	17
-	-	-	1.00%	-	-	-	-	4	230	-4
0.62%	-	-	1.00%	-	-	-	-	263	230	-32
-	-	-	-	-	-	-	-	257	7	173
-	-	-	-	2.17%	-	-	2.99%	59	235	182
-	1.81%	-	2.00%	-	-	4.17%	-	-67	52	-118
-	-	-	-	-	1.06%	-	-	122	-78	147
32.92%	18.67%	-	-	6.52%	6.38%	-	-	306	116	48

Appendix 2 *Eucalyptus* plot species composition, DCA site and species scores, total number of observations, species movement type and percentage of observations for each site, vegetation type and season for all eucalypt sites during the 2011–2012 survey period.

Site			Barnong	Lochada	Darwin	Buntine	Barnong	Lochada	Darwin	Buntine
Vegetation			Eucalyptus							
Season			Winter				Spring			
DCA Axis 1 Sample Score			72	49	37	44	319	148	83	64
DCA Axis 2 Sample Score			83	19	22	82	66	32	99	42
DCA Axis 3 Sample Score			35	63	160	29	179	133	203	85
Total Number of Observations			150	131	88	81	922	218	247	112
Common name	Scientific name	Movement type								
Australian magpie	*Cracticus tibicen*	Loc.Disp.	-	-	-	-	-	-	-	-
Australian raven	*Corvus coronoides*	Sedentary	3.95%	-	3.41%	2.47%	0.33%	2.78%	0.81%	9.09%
Australian ringneck	*Barnardius zonarius*	Sedentary	1.32%	9.92%	1.14%	-	-	11.11%	4.05%	4.55%
Black honeyeater	*Certhionyx niger*	Nomadic	-	-	-	-	1.19%	-	-	-
Black-eared cuckoo	*Chalcites osculans*	Migratory	1.32%	-	-	-	-	-	1.21%	13.64%
Black-faced cuckoo-shrike	*Coracina novaehollandiae*	Migratory	-	-	-	-	0.33%	-	-	-
Black-faced woodswallow	*Artamus cinereus*	Nomadic	-	-	-	-	0.33%	-	-	-
Bourke's parrot	*Neopsephotus bourkii*	Nomadic	-	-	-	-	-	-	-	-
Brown falcon	*Falco berigora*	Sedentary	-	0.76%	-	1.23%	-	-	-	-
Brown goshawk	*Accipter fasciatus*	Loc.Disp.	-	-	-	-	-	0.46%	0.81%	-
Brown songlark	*Cincloramphus cruralis*	Nomadic	-	-	-	-	-	-	-	-
Budgerigar	*Melopsittacus undulatus*	Nomadic	-	-	-	-	80.80%	12.96%	7.69%	-
Chestnut-rumped thornbill	*Acanthiza uropygialis*	Loc.Disp.	20.39%	14.50%	-	22.22%	0.98%	9.26%	0.81%	12.12%
Cockatiel	*Nymphicus hollandicus*	Migratory	-	-	-	-	3.58%	6.48%	2.02%	-
Collared sparrowhawk	*Accipiter cirrhocephalus*	Sedentary	-	0.76%	-	-	-	-	-	-
Common bronzewing	*Phaps chalcoptera*	Loc.Disp.	-	-	-	-	-	-	-	-
Crested bellbird	*Oreoica gutturalis*	Sedentary	1.32%	4.58%	-	-	0.11%	2.31%	-	-
Crested pigeon	*Ocyphaps lophotes*	Sedentary	-	-	-	-	0.33%	-	-	-
Crimson chat	*Epthianura tricolor*	Nomadic	-	-	-	-	-	-	-	-
Emu	*Dromaius novaehollandiae*	Loc.Disp.	-	-	-	-	-	0.93%	0.40%	-
Galah	*Eolophus roseicapillus*	Sedentary	1.32%	1.53%	18.18%	1.23%	1.74%	2.78%	32.39%	13.64%
Grey butcherbird	*Cracticus torquatus*	Sedentary	1.97%	-	-	-	0.11%	-	-	-
Grey currawong	*Strepera versicolor*	Sedentary	-	-	-	-	-	-	0.40%	-
Grey fantail	*Rhipidura albiscapa*	Migratory	4.61%	4.58%	1.14%	2.47%	-	-	-	-
Grey shrike-thrush	*Colluricincla harmonica*	Sedentary	1.97%	2.29%	2.27%	1.23%	0.22%	0.93%	2.43%	6.06%
Horsfield's bronze-cuckoo	*Chalcites basalis*	Migratory	-	-	1.14%	1.23%	-	0.46%	0.40%	-
Inland thornbill	*Acanthiza apicalis*	Loc.Disp.	13.82%	3.82%	5.68%	19.75%	0.11%	3.24%	5.26%	12.12%
Jacky winter	*Microeca fascinans*	Loc.Disp.	0.66%	-	1.14%	1.23%	-	-	-	1.52%
Little button-quail	*Turnix velox*	Sedentary	-	-	-	-	-	-	-	1.52%
Little eagle	*Hieraaetus morphnoides*	Sedentary	-	-	-	-	-	-	-	-
Major Mitchell's cockatoo	*Lophochroa leadbeateri*	Sedentary	-	4.58%	-	-	-	-	0.40%	-
Mulga parrot	*Psephotus varius*	Sedentary	1.32%	-	-	-	0.98%	-	0.81%	1.52%
Nankeen kestrel	*Falco cenchroides*	Sedentary	-	-	-	-	-	-	-	-
Pallid cuckoo	*Cacomantis pallidus*	Migratory	-	-	1.14%	-	0.11%	2.78%	-	-
Pied butcherbird	*Cracticus nigrogularis*	Sedentary	-	-	3.41%	-	-	2.31%	0.40%	-
Rainbow bee-eater	*Merops ornatus*	Migratory	-	-	-	-	-	-	-	-
Red wattlebird	*Anthochaera carunculata*	Nomadic	-	-	1.14%	-	-	-	1.21%	-
Red-backed kingfisher	*Todiramphus pyrrhopygius*	Nomadic	-	-	-	-	0.33%	0.93%	-	-
Red-capped robin	*Petroica goodenovii*	Loc.Disp.	17.76%	12.21%	5.68%	9.88%	2.17%	7.41%	2.43%	4.55%
Red-tailed black-cockatoo	*Calyptorhynchus banksii*	Nomadic	-	-	9.09%	-	-	5.09%	-	-
Redthroat	*Pyrrholaemus brunneus*	Sedentary	-	-	-	-	-	-	-	4.55%
Regent parrot	*Polytelis anthopeplus*	Nomadic	-	-	4.55%	-	-	-	5.26%	-
Rufous tree-creeper	*Climacteris rufa*	Sedentary	-	-	4.55%	-	-	-	2.02%	-
Rufous whistler	*Pachycephala rufiventris*	Loc.Disp.	0.66%	2.29%	-	-	0.22%	-	0.81%	1.52%
Singing honeyeater	*Lichenostomus virescens*	Nomadic	-	-	-	2.47%	-	-	-	-
Southern whiteface	*Aphelocelphala leucopsis*	Sedentary	12.50%	2.29%	-	-	-	6.02%	-	-
Spiny-cheeked honeyeater	*Acanthagenys rufogularis*	Nomadic	-	-	-	2.47%	0.43%	2.31%	-	16.67%
Splendid fairy wren	*Malurus splendens*	Loc.Disp.	1.32%	-	-	-	-	-	-	-
Striated pardalote	*Pardalotus striatus*	Migratory	-	1.53%	2.27%	-	-	0.46%	-	-
Tawny frogmouth	*Podargus strigoides*	Sedentary	-	-	2.27%	-	-	-	0.40%	4.55%
Tree martin	*Petrochelidon nigricans*	Migratory	-	-	2.27%	-	-	-	11.74%	-
Varied sittella	*Daphoenositta chrysoptera*	Sedentary	2.63%	-	-	-	-	-	-	-
Weebill	*Smicrornis brevirostris*	Sedentary	2.63%	29.01%	29.55%	16.05%	1.74%	12.50%	8.10%	45.45%
Western corella	*Cacatua pastinator*	Nomadic	-	-	-	2.47%	-	-	2.83%	-
Western gerygone	*Gerygone fusca*	Sedentary	-	-	-	-	-	-	-	-
Whistling kite	*Haliastur sphenurus*	Nomadic	-	-	-	-	-	-	-	1.52%
White-browed babbler	*Pomatostomus superciliosus*	Sedentary	1.97%	-	-	8.64%	-	-	-	3.03%
White-browed treecreeper	*Climacteris affinis*	Sedentary	-	1.53%	-	-	-	-	-	-
White-eared honeyeater	*Lichenostomus leucotis*	Loc.Disp.	-	-	-	1.23%	-	-	-	-
White-fronted honeyeater	*Purnella albifrons*	Nomadic	-	-	-	-	-	-	-	-
White-winged triller	*Lalage sueurii*	Migratory	-	0.76%	-	-	1.84%	4.17%	2.43%	6.06%
Willie wagtail	*Rhipidura leucophrys*	Loc.Disp.	-	-	-	-	-	-	-	-
Yellow-plumed honeyeater	*Lichenostomus ornatus*	Loc.Disp.	-	-	-	-	-	-	-	-
Yellow-rumped thornbill	*Acanthiza chrysorrhoa*	Sedentary	1.97%	-	-	3.70%	-	0.46%	-	3.03%
Yellow-throated miner	*Manorina flavigula*	Loc.Disp.	3.29%	3.05%	-	-	2.06%	1.85%	2.43%	3.03%
Zebra finch	*Taeniopygia guttata*	Nomadic	-	-	-	-	-	-	-	-

Barnong	Lochada	Darwin	Buntine	Barnong	Lochada	Darwin	Buntine			
Eucalyptus										
Summer				Autumn						
165	109	0	28	41	55	36	37			
101	24	0	100	130	8	86	72			
55	117	88	44	21	90	193	40		DCA Species Scores	
205	169	98	146	126	163	290	84	Axis 1	Axis 2	Axis 3
1.46%	2.05%	-	2.74%	-	-	-	-	146	60	-346
0.98%	1.37%	2.04%	2.05%	1.59%	1.84%	0.34%	1.19%	53	58	50
1.46%	15.07%	4.08%	3.42%	1.59%	9.20%	2.76%	1.19%	95	9	127
-	-	-	-	-	-	-	-	367	99	134
-	0.68%	-	-	-	-	-	-	-11	-39	93
1.46%	-	4.08%	4.11%	-	-	-	-	-132	329	-82
-	-	-	1.37%	6.35%	-	-	-	-131	277	-167
-	-	-	-	1.59%	-	-	-	29	251	172
-	-	2.04%	-	-	0.61%	-	-	21	-26	-176
-	0.68%	4.08%	-	-	-	-	-	37	-52	176
-	0.68%	-	-	-	-	-	-	-	-	-
2.44%	-	-	-	-	-	-	-	352	70	187
10.24%	8.22%	9.18%	7.53%	33.33%	17.18%	10.00%	19.05%	51	100	14
5.85%	16.44%	-	-	-	-	2.41%	-	293	-14	211
-	-	-	-	-	-	-	-	92	-18	-253
-	3.42%	-	2.05%	1.59%	0.61%	-	-	35	82	-63
1.95%	2.74%	-	0.68%	-	-	-	1.19%	176	122	45
0.49%	0.68%	-	-	-	-	-	-	-7	298	46
-	0.93%	-	-	-	-	-	-	286	79	216
-	0.00%	-	-	-	-	-	-	182	54	86
-	4.79%	-	6.16%	3.97%	0.61%	24.83%	5.95%	55	243	241
-	-	-	-	1.59%	1.23%	-	1.19%	-54	105	-47
-	-	-	-	-	0.61%	0.34%	-	131	40	-117
-	-	-	-	-	-	0.34%	11.90%	-94	39	-155
0.98%	1.37%	2.04%	2.05%	-	-	1.72%	1.19%	151	166	131
-	-	-	-	-	-	-	-	264	47	-58
6.83%	2.74%	1.02%	7.53%	2.38%	1.84%	0.69%	7.14%	70	68	-8
-	-	-	-	-	-	-	-	-82	-64	-61
0.98%	-	-	1.37%	-	-	-	-	304	234	17
-	-	-	2.05%	-	-	-	-	-	-	-
-	-	-	-	-	1.23%	-	-	27	-108	-36
3.41%	-	-	-	10.32%	-	-	4.76%	38	293	-88
-	-	1.02%	-	-	-	-	-	45	31	-183
-	-	-	-	-	-	-	-	253	-56	230
-	8.22%	4.08%	-	0.79%	1.84%	2.41%	-	81	-55	222
-	1.37%	-	3.42%	-	-	-	-	328	114	153
-	-	1.02%	0.68%	-	-	-	-	-9	230	-270
-	0.68%	-	-	-	-	-	-	230	-114	219
4.88%	0.00%	1.02%	1.37%	11.90%	4.91%	3.79%	7.14%	138	85	41
-	1.37%	-	-	-	-	1.38%	-	154	-59	231
2.44%	-	3.06%	-	-	1.23%	-	2.38%	220	171	-20
-	-	-	-	-	-	-	-	83	-58	295
-	-	10.20%	-	-	-	3.45%	-	182	320	214
1.95%	-	1.02%	1.37%	-	0.61%	-	1.19%	208	98	-4
1.46%	-	-	6.85%	-	1.84%	2.41%	-	23	367	16
5.85%	-	-	-	3.17%	5.52%	-	-	131	111	138
15.12%	-	-	3.42%	-	-	0.34%	-	238	54	51
4.88%	6.85%	-	-	2.38%	-	-	3.57%	188	199	90
-	-	1.02%	3.42%	-	-	3.10%	-	-74	16	198
-	-	-	-	-	-	-	-	-61	-127	101
-	-	-	-	-	-	21.03%	-	19	32	346
-	-	-	-	-	-	-	-	-	-	-
4.88%	19.86%	36.73%	24.66%	7.14%	30.67%	15.17%	22.62%	-20	-66	131
-	-	-	-	-	-	-	-	76	202	264
0.49%	-	-	-	-	-	-	-	-	-	-
-	0.68%	-	-	-	-	-	-	47	189	-44
1.46%	-	-	6.16%	3.97%	-	-	3.57%	-4	264	17
-	-	-	-	-	1.23%	-	-	-117	-148	-46
-	-	-	2.05%	-	-	1.03%	-	4	230	-4
2.93%	-	-	-	-	-	-	-	263	230	-32
-	-	-	-	-	-	-	-	257	7	173
1.95%	-	-	-	2.38%	-	0.69%	-	59	235	182
-	3.42%	-	-	-	-	-	-	-	-	-
0.49%	-	9.18%	2.05%	3.97%	-	1.38%	-	-67	52	-118
1.46%	9.59%	3.06%	1.37%	-	17.18%	0.34%	4.76%	122	-78	147
10.73%	2.74%	-	-	-	-	-	-	306	116	48

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Aquatic invertebrates of pit gnammas in southwest Australia

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Despite numerous studies on pan gnammas (rock pools) in recent years, the deeper, less-ephemeral pit gnammas remain virtually unknown except for their geomorphology. This study examined 50 pit gnammas in the Wheatbelt and adjacent Goldfields over 2010–2012 and found 82 taxa of invertebrates rich in insect variety but dominated numerically by a few crustaceans. Mean momentary species richness per pool averaged 8.2 (range 1.5–16.2), with more in larger pools and some clumped pools, and fewer in pools covered by rock slabs or with water flow through them. Pools across the study area showed a minor change in species composition from the northwest to south. In a comparsion with pan gnammas, the distinctive physicochemical environment of pit gnammas is also largely determined by their location on granite outcrops, but their differing history and origins and hence hydrological environment have resulted in major differences in their invertebrate fauna. Pans are more species rich than pits, and have many endemic species, mainly crustaceans, but also a few insects, adapted to the regularly desiccating environment and subjected to strong UV rays. Fluctuating climates over millennia coupled with poor dispersal have promoted speciation among these crustaceans. By contrast, the more persistent pit gnammas support eurytopic species mostly easily dispersed, though two species of the clam shrimp *Lynceus* are characteristic.

KEY WORDS: Cladocera, gnammas, *Lynceus*, hydrology, insects, Ostracoda, physicochemical environment.

INTRODUCTION

Early studies of some gnammas on granite outcrops in the southwest of Western Australia recognised the interesting biological adaptations to living and surviving desiccation in these pools with their short hydroperiods and long periods of dryness. These included autecological studies by Edward (1968, 1989) and Jones (1971, 1974) on dipterans, especially *Paraborniella tonnoiri*, and taxonomical studies such as Fairbridge (1945), Cranston & Edward (1987), Frey (1998), Smirnov & Bayly (1995), Benzie & Bayly (1996), Hendrich & Fery (2008), Zofkova & Timms (2009) and Timms (2013b) on various invertebrates specific to rock pools. Later, community ecology with particular reference to the rich diversity of invertebrates was investigated (Bayly 1982, 1997; Pinder *et al.* 2000; Timms 2006; Jocqué *et al.* 2007a).There has also been considerable effort on similar pools overseas (Jocqué *et al.* 2007b, 2010a; Vanschoenwinkel *et al.* 2009) often with particular reference to interactions between faunal elements (Pajunen & Pajunen 1993; de Roeck *et al.* 2005; Jocqué *et al.* 2010b). It is now recognised that the fauna of gnammas of southwestern Australia is the most diverse of any inland rock pools anywhere, and with an array of adaptations and faunal interactions (Jocqué *et al.* 2010a).

However these comments apply only to the common shallow pan gnammas. The deeper pit gnammas (Twidale & Corbin 1963), with longer hydroperiods and generally shorter periods of dryness, have hardly been studied (Bayly 2002). One on Dingo Rock near Wongan Hills was included in the Pinder *et al.* 2000 study (A Pinder pers. comm. 2012); Bayly (1997) studied one on War Rock near Morewa; Zofkova's (2006) work on the phylogeography of the pea shrimp *Lynceus* centred on species in pit gnammas in the Wheatbelt; and there is ongoing work on their ostracods (S Halse & K Martens pers. comms. 2011) and *Lynceus* (Timms 2013a). The geomorphology of pit gnammas is more complex than that of pan gnammas (Twidale & Vidal Romani 2005; Timms 2013b), but to date it seems their ecology is simpler (i.e. fewer species, fewer endemics, no special adaptations).

Pan gnammas in the Wheatbelt and adjacent Goldfields of southwestern Australia support a rich aquatic fauna dominated by crustaceans many of which are endemic to them (Bayly 1982, 1997; Pinder *et al.* 2000; Timms 2006; Jocqué *et al.* 2007a). This fauna is adapted to a distinct hydrological environment of filling in winter and drying in summer, and diversified by refugial response to a long history of climatic fluctuations (Pinder *et al.* 2000). At the local scale, community composition is affected by gnamma size, bigger pools having more species (Vanschoenwinkel *et al.* 2009), and density of pools on an outcrop and nearness to other rock outcrops expressed by enhancing dispersion when other pools are close by (B Vanschoenwinkel pers. comm. 2010). Also climatic gradients are another determinant of community structure, so that species richness decreases northwards and northwestwards with less reliable and shorter fillings of the gnammas (Timms 2012a, b). The ultimate restriction is seen in the depauperate fauna of desert pipe gnammas (another type of gnamma which are deep narrow shafts of water in non-granitic rocks) in eastern Western Australia with their small surface areas and extreme isolation greatly diminishing the arrival and survival of dispersers (Bayly *et al.* 2011).The third major type of rock waterhole are pit gnammas that are generally deeper, hemispherical in profile, less common and more isolated and importantly not so closely tied to the seasonal hydrological pattern characteristic of pan gnammas (Timms 2013b). Their aquatic fauna would expected to be not so specialised, not so diverse, nor affected as much by climatic gradients; in fact more akin to the fauna of any small waterbody regionally. Size would be expected to greatly influence species richness and there may be some influence of relative isolation on faunal composition.

In the past, pan and pipe gnammas have been characterised by the number of species they support (species richness) and their species composition. Multivariate analysis is increasingly being used to differentiate metacommunities (Timms 2012a, b). All analyses rely upon comparative sampling effort, something difficult to achieve for small temporary habitats. The third major type of gnammas, the deeper less-ephemeral pit gnammas, have not be studied, either in their general limnological features or in their faunal composition. The aims of the present study are to characterise the limnology of these pit gnammas in the southwest of Western Australia with special reference to assessing invertebrate communities and the major factors which influence species richness and community structure. This will be done in the context of comparison with the more common pan gnammas.

METHODS

Pit gnammas are sparsely distributed across southwestern Australia, with most granite outcrops lacking them or having only one or two, as opposed to numerous pan gnammas on most (Timms 2012a, b). Fifty of the 80 gnammas known to the author in the northern and eastern Wheatbelt and adjacent Goldfields (Timms 2013b) were chosen for limnological study (Figure 1). Choice of study gnammas was not random, but based on accessibility, background knowledge on each, and achieving a variety of sizes, geomorphic types and district locations. Each was visited four to five times from October/November 2010 to August 2012 initially covering drought conditions then more normal seasonal conditions in July to September 2011 and August 2012. This enabled most to be seen dry, partly filled and completely filled, and all were sampled when water was present at four or five times.

On each visit a water sample was taken to determine conductivity in µS/cm with an ADWA332 conductivity meter and turbidity was measured in a Secchi disc tube calibrated in Nephrometric Turbidity Units (NTU). Depth was determined with a stout tape measure and when a pit was deemed full its length and width measured and volume was calculated (Timms 2013b). On the September 2011 trip, pH was determined with Hanna HI8924 meter. In the calculation of mean pHs, the logarithmic scale was first converted to arithmetic values via antilogs, averaged and then converted back to log values. Various geomorphic types were identified (Timms 2013b), but pertinent to this study were those on waterways—the lotic potholes. All others were considered lentic environments, though the plunge pools experienced significant flushing at times. Also some still had covers remaining from the days when indigenous folk placed covers on gnammas important to them for water supply (Appendix 1).

To sample the fauna, a dip net of 1 mm mesh and 25 cm wide, 20 cm high and 30 cm deep supported on a D frame and carried on a 1.8 m handle was used to catch macroinvertebrates for five minutes and a plankton net of mesh 159 µm, 25 cm wide, 15 cm high and 90 cm long and also carried on a handle 1.8 m long was used to catch zooplankton in the water column for one minute. Species accumulation per unit effort was not assessed, but experience strongly suggested almost all dip-netted species present in small gnammas (V <0.5 m^3) were caught in the first minute, similarly for medium-sized gnammas (V = 0.6–5 m^3) in three minutes, and large gnammas (V>5.1 m^3) in five minutes with some

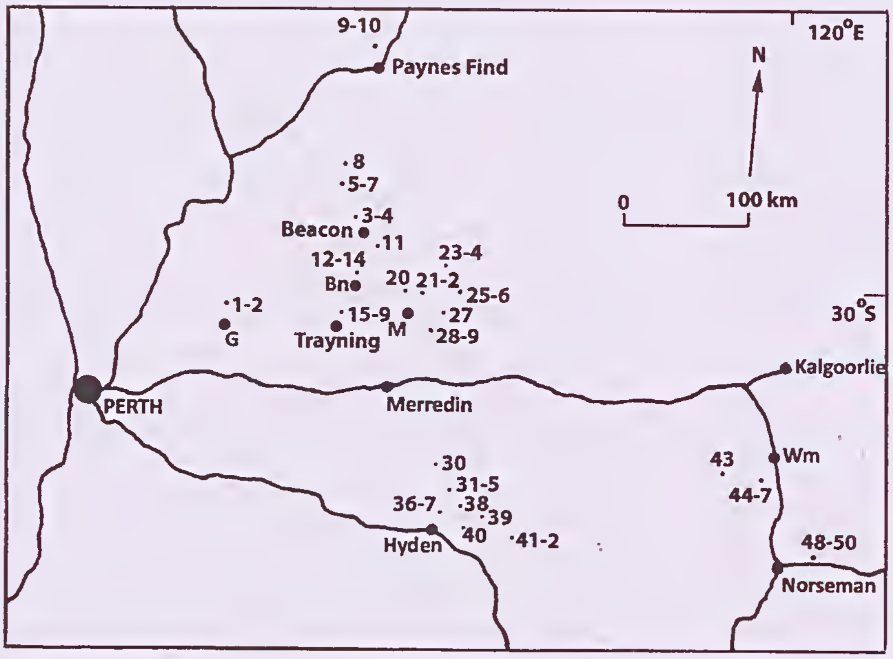

Figure 1 Map of southwestern Australia showing location of the 50 pit gnammas.

exceptions listed below. The pond net collected macroinvertebrates in the littoral, the open water and also the benthic infauna, though in large gnammas wider than 3 m and deeper than 1.5 m (e.g. Weira Gnamma) benthic sampling was inefficient, and in gnammas deeper than 2 m (e.g. Beringbooding North) it was logistically impossible to collect benthic infauna species at all. It is not known how inefficient this sampling was as there were no large gnammas in this series where sampling can be claimed to be truely efficient. Macroinvertebrates were sorted alive in a white tray, and representatives of all species caught were preserved in alcohol for later identification, and the remainder returned alive to the pit, together with all tadpoles caught. The whole zooplankton collection was preserved in alcohol for later study. For small gnammas (V <0.5m^3), much smaller nets of the same meshes were employed for the same time periods.

The 50 pits were arranged into five groups of 9–11 pits each, according to district (northwest, north, northeast, south, east) (Figure 1; Appendix 1), but sometimes on landscape factors (e.g. the two Forestiana pits are close to most members of the south series, but are included with the east series as all the latter are in unfarmed scrub and woodland).

Relationships between these series and between them and pan gnammas in four of the five districts were investigated using PRIMER (v5) (Clarke & Gorley 2001).

To make the data as extensive and comparative as possible, 45 sets of presence/absence records were assembled from 9-11 pit gnammas in the five districts. For pan gnammas, data in Timms (2012a, b) was taken from 10 gnammas on Bullamanya Rock (6, (northwest), Yanneymooning Rock (7, northeast), Hyden Rock (8, south) and three rocks near Norseman (9, east). In the first three of these rocks data were accumulated from visits in June, July, early August, late August and September to give 45 sets; for the Norseman rocks to get 45 sets the three sets of 10 had to be multiplied by 1.5 as there was only one visit to these three rocks. While data assembly is somewhat heterogeneous the aim was to have a similar number for each group based on as many samplings as possible. Species which occurred only once in all nine groupings were ignored as they do not contribute to similarities.

The relationship between pit gnamma size and mean momentary species richness was tested using linear regression, while statistical differences between some gnamma types and their mean momentary species richness was investigated using one-way anosims.

RESULTS

Physicochemical features

Morphometrics of the pit gnammas are examined in detail in Timms (2013b), but it is pertinent to note here that there is a large range in the size of the pits from a volume of 0.04 m^3 to 110 m^3 (Appendix 1), with a mean of 6.18 m^3 and a median of 0.98 m^3. Though all contained fresh water, there was likewise a large range of mean conductivities from 39.3 to 587.2 µS/cm, with a mean value of 149.7 ± 106.1 µS/cm and a median of 115.2 µS/cm. Again the values were skewed with most between 51 and 150 µS/cm (Figure 2a). The three exceptionally high values in Wattoning, Twine Shrub and Buldania West pits (Appendix 1) were for gnammas that apparently rarely overflowed. Contrawise, many of the lowest values were in pits that were covered (Wheelers at 39.3 µS/cm) or on waterways (Cave Rock at 69.6 µS/cm). Conductivities in many pit gnammas varied widely between visits. Large, apparently permanently inundated gnammas exhibited the least variability in conductivities (e.g. Beringbooding North 131–338 µS/cm; Weira 43–153 µS/cm) while many small gnammas which were sampled when almost dry and again when full had the widest variations in conductivity (Trayning Mid 66–540 µS/cm; Yellari North 34–424 µS/cm).

Gnamma waters were generally clear with 74% of values <20 NTU and 42% <10 NTU and with a mean value of 18.8 NTU for all 50 sites (Figure 2b; Appendix 1). A few gnammas occasionally had algal blooms increasing turbidity and some like Yellari North and Buldania East (mean turbidities 108.7 and 91.6 NTU) had major algal blooms on all visits, or most visits (Oak Flat West 37 NTU). Only a few gnammas had turbidities that seemed to be largely influenced by turbid runoff, these being Wiera at 49.6 NTU, Higgensville North at 41.2 NTU, Higgensville Mid at 41.2 NTU and the two Willogyne gnammas at 30.8 and 40.0 NTU. When these eight are ignored the mean turbidity reduced to 8.2 NTU.

All gnammas were neutral to alkaline (pH range 7.0–8.8, mean 7.49) on the September trip in 2011.

Biological features

Eighty-two taxa were found in the 50 gnammas, many species occurring sporadically and many rarely (Table 1). Sixteen percent of species occurred just once, 34% were found up to three times, and 49% of species occurred five times or fewer. The most widespread and common species were, in order: ostracods *Cypericercus* spp., the boatman *Agraptocorixa parvipunctata*, the dytiscid *Sternopriscus multimaculatus*, the midge *Chironomus tepperi*, the copepod *Boeckella triarticulata*, the boatman *Micronecta gracilis*, the pea shrimp *Lynceus magdaleanae*, the cladoceran *Moina australiensis* and the backswimmer *Anisops thienemanni*. If this list is extended to include all those species with more than 25 records, then of the 23 species, 16 are insects and 7 crustaceans. Of the full list, there are 54 insects, 25 crustaceans, 4 molluscs, 3 turbellarians, 3 rotifers, 2 arachnids and 1 oligochaete.

Distribution of species across the study region is uneven, even for common species (Table 1). Most noticeable is the absence or major restriction of many species in the south plus east districts. Examples include *Lynceus baylyi, Moina australiensis, Boeckella triarticulata* and *Antiporus gilberti*. The southern district, which includes six gnammas on Twine Rock has a restricted fauna, with *Lynceus magdaleanae,* many beetles, bugs and molluscs comparatively uncommon (Table 1) But other species such as *Mesocyclops* cf. *notius, Hemicordulia tau, Anisops hyperion* and *Chironomus alternans* were unusually common (Table 1).

Multivariate analysis of each gnamma's fauna showed many of the gnammas in each group were closely allied and furthermore suggested a minor trend from

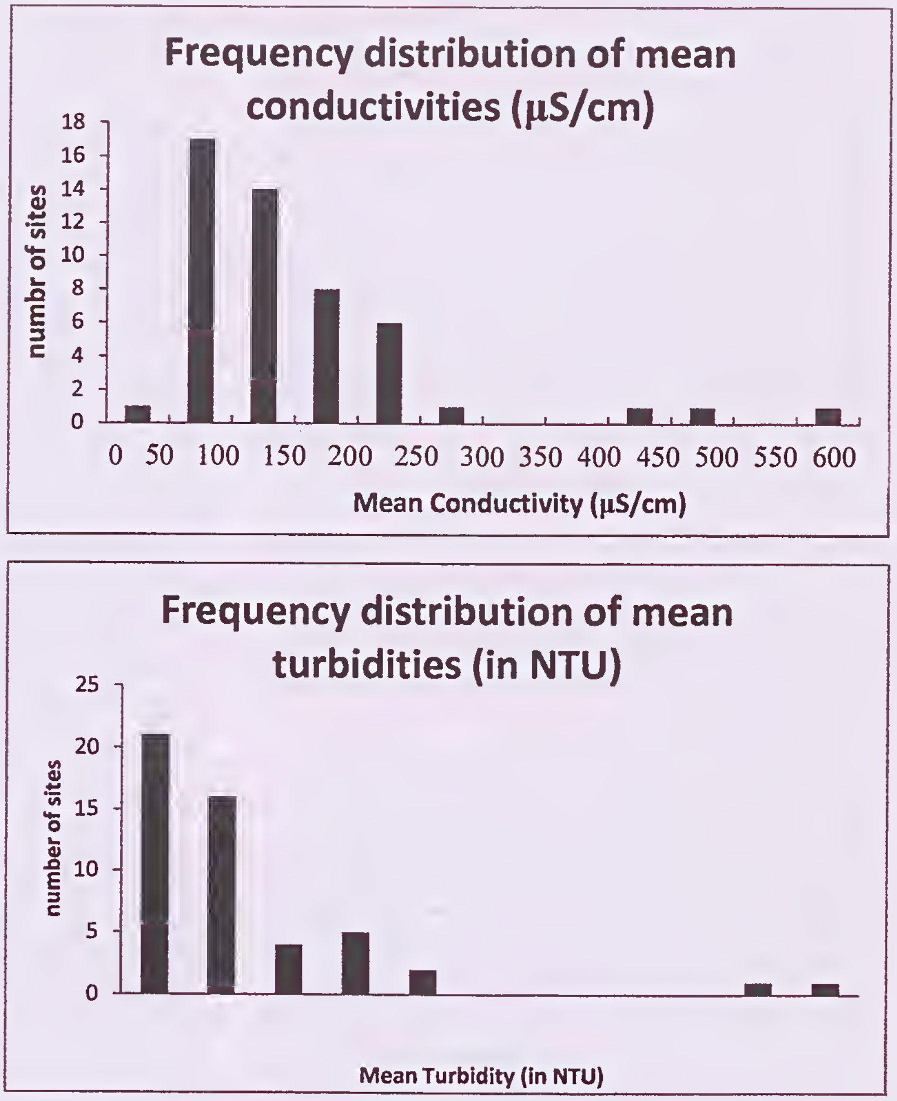

Figure 2 (a) Frequency distribution of mean conductivities (in µS/cm). (b) Frequency distribution of mean turbidities (in NTU).

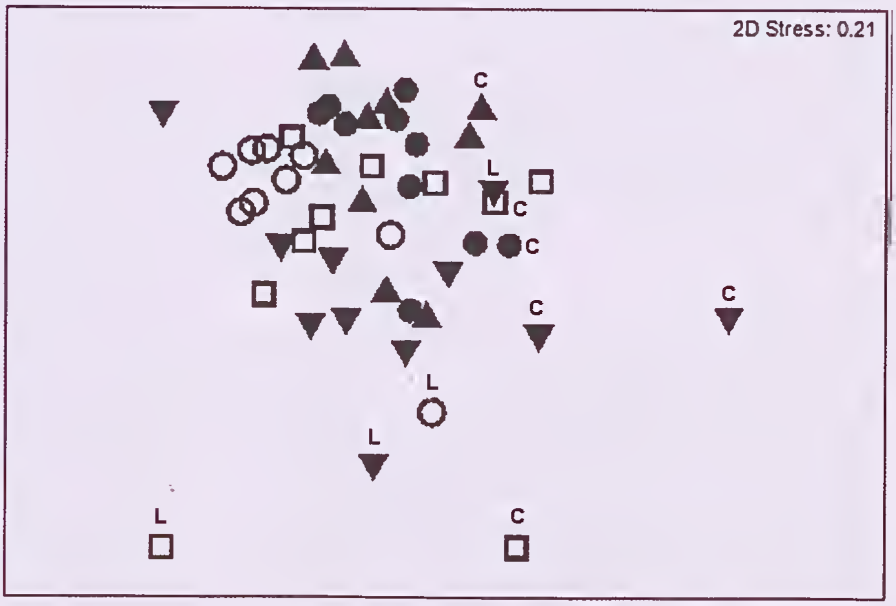

Figure 3 nMDS plot of relationships of invertebrate communities in the 50 gnammas. ▲, 10 gnammas in the northwest district; ●, 10 gnammas in the northdistrict; ○, 9 gnammas in the northeast district; ▼, 11 gnammas in the south district; □, 10 gnammas in the southeast district; C, covered gnammas; L, lotic gnammas.

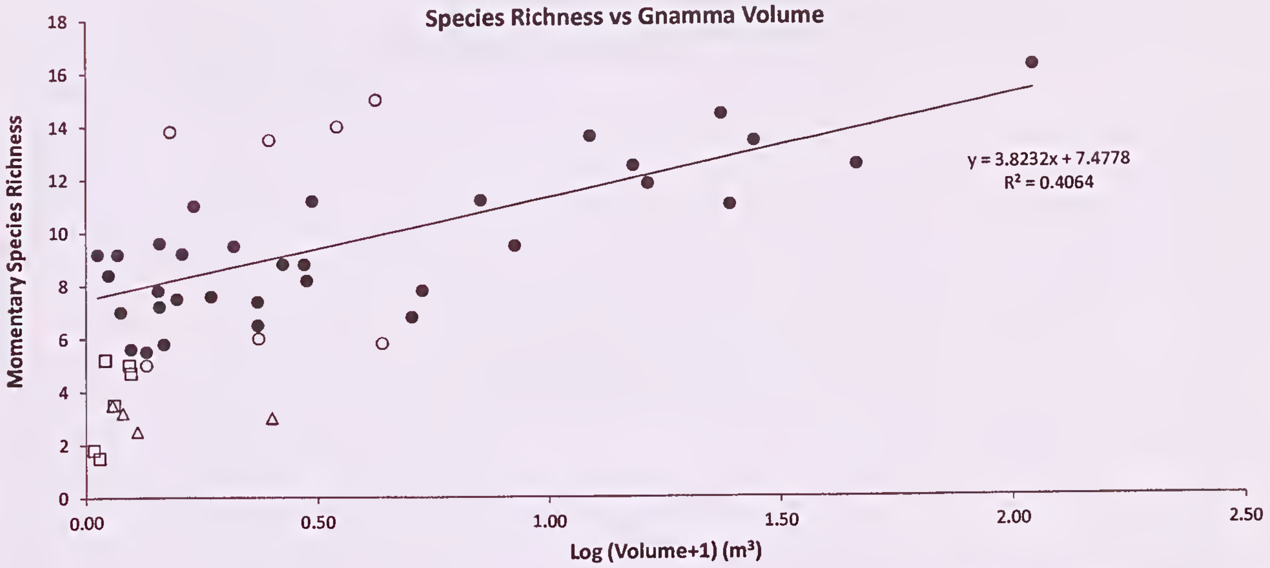

Figure 4 Relationship between mean momentary species richness and gnamma volume. ●, normal gnammas; ○, normal gnammas well removed from trend line; □, covered gnammas; △, lotic gnammas.

northwest to south, though the remote east gnammas clumped with north gnammas (Figure 3). One-way anosims of all possible pairings between the five districts showed differences between each were mostly significant at 5% (r = 0.112–0.406) for all except the northwest and north pair (r = 0.009) and the south and east pair (r = 0.068). This nMDS plot also suggests some gnammas lie outside the main clump; these are the covered and lotic gnammas discussed later.

Larger gnammas, by volume, supported more species, the correlation (r = 0.4064) being significant at P <0.001. for the 40 normal gnammas (i.e. those uncovered and lentic) (Figure 4). The regression line for this relationship is highly significant (P <0.000001). This is despite some very large gnammas not being sampled effectively and hence not as speciose as might expected. The impact of the 'missing' species on the relationship at the large end of the relationship could not be tested easily, but at the other end of the scale some of the large variation in species richness is testable. The apparent negative influence of gnamma cover plates and location on a waterway is testable. For the unusual covered and lotic gnammas there was no relationship between species richness and size (Figure 4), and when compared respectively to covered and lentic pools of the same size, both showed a significantly reduced fauna (Figure 5a, b). All pairings are significantly different at P = 0.05 or better (Table 2).

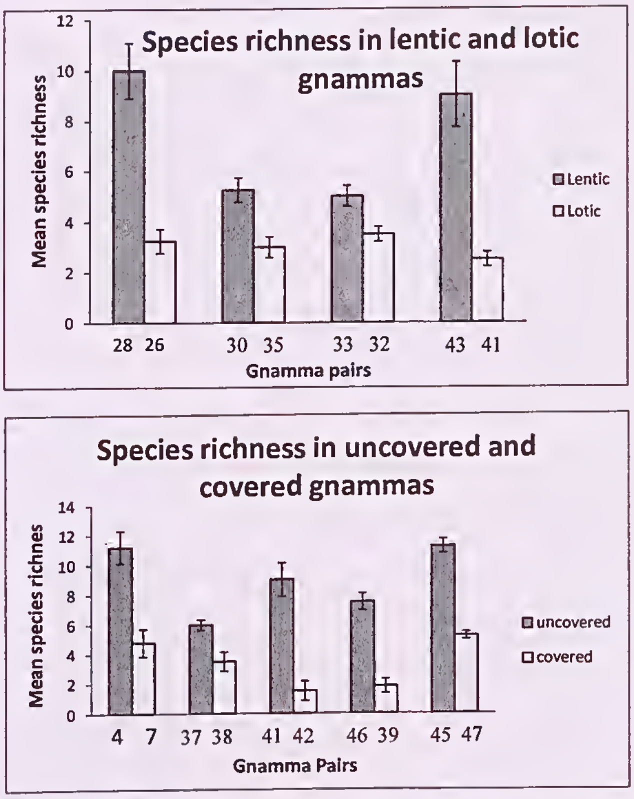

Figure 5 (a) Species richness in paired lentic and lotic pit gnammas. (b) Species richness in paired uncovered and covered pit gnammas.

Other gnammas somewhat different from the normal (i.e. uncovered and lentic) gnammas are shown in open circles on Figure 4. There are four with mean species richness well above what might be expected for their size and at least three with species richness below expectations (there are more slightly less extreme than these, but there is no easy explanation for their deviation). Three of the four above the line are in the Trayning series, a closely spaced series of five gnammas at about 1–5 m intervals along a rock joint (Timms 2013b) and the other one is Buldania East Gnamma, part of a group of three gnammas about 30–40 m apart. The inference here is that closely spaced gnammas accumulate more species because dispersal is more efficient over short distances. However the effect was not significant when tested in a best case scenario [five Trayning pits in a row less than 30 m end to end and averaging 2.1 m apart compared to five other pans (Oak

Table 1 Number of records of invertebrates in the 50 pit gnammas.

Taxa	Northwest	North	Northeast	Hyden	Norseman	Total
Turbularia						
unident planarian 'grey'	1	-	3	-	2	6
unident. planarian 'black'	2	1	1	-	-	4
unident. planarian 'flat green'	4	-	-	-	5	9
Oligochaeta						
Limnodrilus hoffmeisteri	3	8	6	1	-	18
Rotifera						
Asplanchna sp.	-	1	4	-	-	5
Brachionus spp.	1	-	6	1	-	8
Keratella australis	-	-	5	-	-	5
Branchiopoda						
Branchinella affinis	1	-	-	-	-	1
Lynceus baylyi	24	26	-	-	-	50
Lynceus magdaleanae	11	8	26	5	17	67
Paralimnadia badia	-	-	-	-	4	4
Eulimnadia ?dahli	1	-	-	-	-	1
Caenestheriella mariae	2	-	-	-	-	2
Triops australiensis	1	-	-	-	-	1
Cladocera						
Daphnia jollyi	-	-	-	-	1	1
Daphnia carinata	6	3	6	-	4	19
Simocephalus acutirostratus	1	-	-	-	-	1
Moina australiensis	16	22	13	8	7	66
Alona spp.	2	-	2	1	-	5
Copepoda						
Boeckella opaqua	-	-	-	-	4	4
Boeckella triarticulata	20	15	33	1	3	72
Mesocyclops cf *notius*	10	4	7	13	4	38
Macrocyclops sp.	-	-	3	-	-	3
Ostracoda						
Bennelongia sp.	1	-	1	-	-	2
Candonocypris novaezealandiae	1	5	4	6	2	18
Cypretta baylyi	-	-	3	-	2	5
Cypricercus spp.	22	28	12	25	19	106
Heterocypris sp.	12	10	5	1	5	33
Ilyodromus amphicolis	2	3	-	2	2	9
Ilyodromus spp.	-	1	1	-	-	2
Sarscypridopsis sp.	1	-	1	-	-	2
Decapoda						
unident. Parastacidae	-	-	-	1	-	1
Odonata						
Austrolestes analis	-	-	3	-	-	3
Ischnura heterostricta	4	1	5	1	3	14
Hemianax papuensis	3	-	5	-	1	9
Hemicordulia tau	2	4	16	20	4	46
Orthetrum caladonicum	5	4	7	8	4	28
Trapezostirma leowii	-	-	2	-	-	2
Ephemeroptera						
Cloeon sp.	1	-	-	-	1	2
Hemiptera						
Micronecta gracilis	15	14	21	11	9	70
Agraptocorixa parvipunctata	22	28	24	14	13	101
Sigara mullaka	-	-	-	-	1	1
Anisops gratis	3	10	21	6	8	48
Anisops hyperion	4	5	3	12	9	33
Anisops stali	9	4	15	3	2	33
Anisops thienemanni	7	11	22	11	11	62
Trichoptera						
Triplectides ?australis	4	1	13	7	4	29

Taxa	Northwest	North	Northeast	Hyden	Norseman	Total
Coleoptera						
Allodessus bistrigatus	4	5	5	-	2	16
Allodessus larvae	3	2	-	-	2	7
Antiporus gilberti	13	10	16	4	7	50
Antiporus larvae	10	13	13	2	4	42
Berosus spp. (inc. *B. nutans)*	12	2	3	1	4	22
Berosus larvae	2	-	1	-	2	5
Cybister tripunctatus	-	-	1	-	-	1
Enochrus maculipes	-	-	1	3	1	5
Eretes australis	8	7	8	2	6	31
Eretes larvae	1	-	-	2	1	4
Hyphydrus elegans	2	3	12	2	-	19
Hyphydrus larvae	-	3	1	2	1	7
Lancetes lanceolatus	1	1	1	-	2	5
Lancetes larvae	-	-	-	-	2	2
Limnoxenus zelandicus	3	4	2	-	2	11
Limnoxenus larvae	-	2	1	-	-	3
Megaporus howitti	-	-	1	-	-	1
Megaporus larvae	-	-	1	-	-	1
Necterosoma darwini	1	3	7	-	-	11
Necterosoma larvae	2	-	-	-	-	2
Rhantus suturalis	3	3	2	3	-	11
Rhantus larvae	-	2	-	1	-	3
Sternopriscus multimaculatus	21	29	18	13	19	100
Sternopriscus larvae	2	3	4	3	2	14
Diptera						
Chironomus alternans	3	8	1	10	3	25
Chironomus occidentalis	1	-	-	-	-	1
Chironomus tepperi	19	14	20	16	14	83
Cryptochironomus sp.	1	-	4	2	3	10
Dicrotendipes sp.	-	-	-	2	-	2
Paraborniella tonnoiri	-	-	3	1	1	5
Polypedilum nubifer	-	-	1	-	-	1
Procladius sp.	2	-	-	-	-	2
Tanytarsus sp.	-	1	4	-	1	6
unident. Chironomidae	2	1	2	2	1	8
Aedes occidentalis	13	15	6	16	2	52
Aedes notoscriptus	-	-	-	4	-	4
Anopheles annulipes	-	-	-	1	-	1
Culex australicus	-	-	-	1	-	1
unident. Ceratopogonidae	4	4	7	3	3	21
unident. Stratiomyidae	6	2	6	-	1	15
Acarina						
unident. Eyladidae	1	4	3	1	-	9
unident. Hydrachnidae	-	1	2	-	-	3
Gastropoda						
Glyptophysa sp.	-	-	-	1	-	1
Isidorella sp.	-	11	-	-	-	11
Physa acuta	-	-	12	-	6	18
Bivalvia						
Musculium sp.	-	3	4	-	-	7

Flat East,Oak Flat West, Yellari North, Yellari Suth, Remlap) of similar volume and much further apart (averaging 18 km) from adjacent pit gnammas]: mean CSR was 24.6 in the Trayning series and 19.2 in the comparison series but Student t was 0.1083 and not significant even at P = 10%.

The three below the regression line are Bullamanya North, Bullamanya South and Twine North, all plunge pits (Timms 2013b) and so subject to strong flowthrough at times. The inference here is that sometimes these gnammas are subject to scouring and possible loss of species. There are no suitable controls to test this, but the effect is slight and unlikely to be significant.

While there is a high degree of similarity in faunal composition between the 40 normal gnammas and even the 10 unusual covered and lotic pans (Figure 3), pit gnammas support a fauna very dissimilar to that in pan gnammas (Figure 6). This is despite the comparison not

Table 2 Student t values for gnamma pairings in Figure 5.

Pairings	t value
Covered *vs* uncovered (Figure 5b)	
4 & 7	0.0035
37 & 38	0.0160
41 & 42	0.0020
46 & 39	0.0064
45 & 47	0.0007
Lentic *vs* lotic (Figure 5a)	
26 & 28	0.0012
35 & 30	0.0117
33 & 32	0.0240
41 & 43	0.0027

being perfectly matched (e.g. though numbers of each type are in groups of 10, sampling intensity is different and there are representatives of pans in only four of the five districts).

During the drought of 2010 and occasionally at other times, dead vertebrates (lizards, snakes, emus, kangaroos) were observed in 10 pits with multiple drownings in Yellari North, Quanta Cutting, Weira, Twine Mid, and Buldania East, all deep gnammas with steep sides. In fact such gnammas present a hazard to humans, so authorities have filled in some (e.g. at War Rocks via Morewa, and Dingo Rocks via Wongan Hills) or fenced others (e.g. Jibberding Rocks via Wubin, Moningarin gnammas via Cadoux, and one at Buldania Rocks), thus reducing the number of bigger, deeper gnammas available for study.

DISCUSSION

Physicochemical features

Many of the characteristic physicochemical features of pit gnammas are determined by their morphometry and relationship to their catchment, as for most waterbodies (Wetzel 1975). The majority have small catchments of exposed granites and hence incoming waters are of low salt content and clear. Exceptions occur when inflowing waters come from further afield and carry salts and solids. Deep impervious rock basins prevent loss of water and salts, so gnammas tend to act like rain gauges, loosing water mainly by evaporation. Those with covers often have lower conductivities as a cover slows water loss, so in past times when indigenous people placed covers over many gnammas (Bayly 2002; Twidale & Vidal Romini 2005), it is possible conductivities in many more pit gnammas were lower, and fluctuations less. Under present climatic conditions in southwestern Australia many gnammas occasionally overflow and so lose some accumulated salts. Lotic potholes along waterways also tend to have lower conductivities as in these no accumulation of salts is possible, except briefly in droughts. Also, gnammas like Beringbooding North that hold water permanently have lower fluctuations in conductivities than those like Trayning Mid which dry seasonally. Data on conductivities are too infrequent to analyse for seasonal changes from filling to drying, but undoubtedly there is concentration of salts as pit gnammas dry, a fact noted by Bayly (2001) for a rockhole in central Australia and also in pan gnammas in the Wheatbelt (Timms 2012a). Despite some higher values persistently or temporarily in these gnammas, water is always fresh and of characteristically low salinity which is important for the survival of freshwater invertebrates, given most of the surrounding waters on the plains are now saline. This feature they share with the pan gnammas on similar granite outcrops, though average conductivities are a little higher (Pinder *et al.* 2000; Timms 2012a).

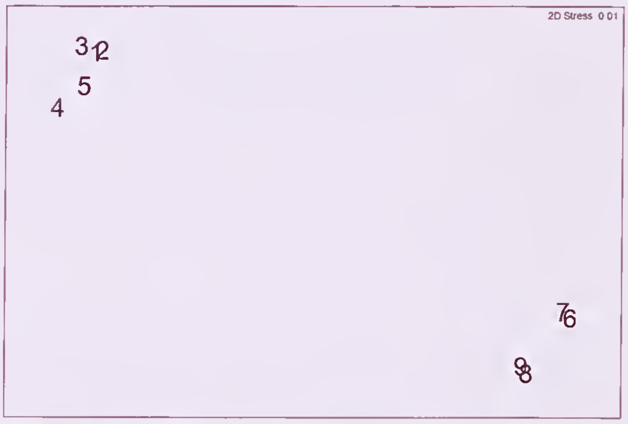

Figure 6 nMDS plot of relationships of invertebrate communities in the 50 pit gnammas arranged in five groups and four groups of pan gnammas. 1, northeast district; 2, north district; 3, northwest district; 4, south district; 5, southeast district; 6, Bullamanya Rock; 7, Yanneymooning Rock; 8, Hyden Rock; 9, three rocks near Norseman.

Also shared with pan gnammas is the clear waters in most pit gnammas, though they are not crystal clear as in almost all pans [mean of 3.1 NTU for 9 pans (Pinder *et al.* 2000) compared with a mean of 9.2 NTU for 42 pits unaffected by extraneous factors]. Exceptions occur when inflowing water is sourced from non-granitic catchments and slugs of nutrients added when large vertebrates fall in and die, as observed during the 2010 drought. So while nutrients are low in pan gnammas (Pinder *et al.* 2000) it seems they could be higher in at least such pits, with the consequence of persistent algal blooms and opaque waters.

For the present 50 pit gnammas the pH ranges from 7.0 to 8.8 with a mean of 7.49. Concordantly, the pH of the sole pit gnamma [War Rock (b)] examined by Bayly (1997) was 7.9. In contrast, the pH of the 34 pan gnammas other than Coragina (a) (Bayly 1992) studied by Bayly (1997) ranged from 4.6 to 7.3 with a mean of 6.49. There is clear evidence, therefore, that the water of pit gnammas is generally alkaline and that of pan gnammas typically acidic. This suggests pit gnammas are less influenced by their acidic granitic base than pans perhaps due to separation by abundant bottom sediment (Timms 2013b) and/or in some cases due to salts from larger catchments/accumulated vertebrate bodies.

Biological features

Cumulative species richness for pools in a defined study area depends on many factors particularly the number of sampling occasions, the number of pools sampled, taxonomic resolution and the size of the area sampled, thus making meaningful comparisons between various studies difficult. This study of pit gnammas across the Wheatbelt and into the Goldfields recorded 82 species whereas Pinder *et al.* (2000) found 230 species in pan gnammas and associated waterholes in the same area, but from more pools and with wider and better taxonomic resolution. In an intensive study of 10 pans each on three rocks in the Wheatbelt, momentary species richness (MSR) averaged 30.75 species on Mt Madden, 26.5 species on Hyden Rock and 29.5 species on Yanneymooning Rock (Timms 2012a).The highest figures for MSR in this study were 16.2 in Beringbooding North and 14.4 in Melancobbing, both large pits, with an average value of 8.2 for the 50 pits, as there were many small gnammas with few species. The conclusion then is pan gnammas support more species than pit gnammas, though the exact difference is unknown. In both types of gnammas, bigger sites support more species [Vanschoenwinkel *et al.* (2009) for pans and this study on pits], but the effect of rainfall gradients on richness in pans (Timms 2012a, b) is not seen in pits. In pit gnammas variation in size and some habitat factors such as presence or absence of a cover and location on a waterway are the most important determinants of MSR, and these act inconsistently across the Wheatbelt. It is possible that many pit gnammas now are more species rich, especially of mobile insects, since European settlement as in the past Aborigines covered many with rock slabs or vegetation to reduce water loss (Bayly 2002), but in reality reducing access to dispersing invertebrates.

The only other studies on deeper gnammas have been by Bayly (1997) on War Rock in the Northern Wheatbelt, Bayly *et al.* (2011) on pipe gnammas in laterite (which provide a similar habitat as pit gnammas) in the Victoria Desert of southeastern Western Australia and Bayly (2001) on a pit (canoe variety) 90 cm deep in central Australia. Bayly (1997) with one visit found just four species in the War Rock pit, but significantly two of these, *Boeckella triarticulata* and *Lynceus* sp. rarely occurred in all his pan gnammas. The author has visited this gnamma three times and found 20 species cumulatively including these two non-pan species (and thus showing the value of multiple samplings, but not included in this data set as there was not the adopted standard of four samplings). Those gnammas isolated in the Victoria desert averaged 4.6 species and the central Australia pit had 9 species after 10 samplings, all somewhat fewer than the present pit gnammas of similar size. As Bayly *et al.* (2011) noted, isolation plays a major role in these desert pools. Some of the present series of pit gnammas are relatively close together, and moreover near pan gnammas with which they share many insects (see later), so they could have more species than normal because of a nearby source of dispersers. This was observed in the Trayning gnammas and one Buldania gnamma (Figure 4).

Two of the species, *Limnodrilus hoffmeisteri* and *Physa acuta* are exotic, often occurring in adjacent gnammas (e.g. *P. acuta* occurs in many gnammas in the northeast district), but neither are widespread and both have notable absences (*P. acuta* in the north and northwest; L. *hoffmeisteri* in the east and almost all of the south districts). Hardly any species are endemic to the pit gnammas, exceptions being the pea shrimps, *L. baylyi* and *L. magdaleanae* (previously misidentified as *L. macleayanus* in Timms 2006: Zofkova & Timms 2009 and Bayly *et al.* 2011) which occur only in gnammas, but also outside the study area (Timms 2013a). There are also some new ostracod species in the genera *Bennelongia* and *Heterocypris*, but some of these are not specific to pit gnammas (K Martens pers. comm. 2013)

This is the first time a sphaeriid bivalve has been found in a gnamma: *Musculium* sp., probably *M. kendricki*, the only species recorded in Western Australia. It is uncommon, found only in a few rivers along the southwest coast (Korniushin 2000) and once in the Wheatbelt (A Pinder pers. comm. 2013). Now there are three more locality records from the Wheatbelt, Trayning North, Melancobbing and Weira gnammas, all in the north and northeast districts. The response of this species to desiccation is unknown (some sphaerids can tolerate desiccation, others cannot: Burch 1975; Clarke1981), but it is noteworthy that the only gnammas it was found in did not dry during the 2010 drought while all other gnammas in the north and northeast areas did. Also its occurrence in just three gnammas and lack of spread to the other nearby Trayning gnammas, may indicate poor dispersal ability. This is explained by waterfowl, their main vectors, being uncommon visitors to deeper rocky waterholes (B V Timms unpubl. data).

Comparison of pit and pan gnammas

Morphologically pit and pan gnammas are very different, pans being shallow saucer-like rock-holes and pits are deeper, generally hemispherical-shaped hollows (Twidale & Vidal Romani 2005; Timms 2013b). Both are formed by water rotting granite; in pans the rotting is directed horizontally along laminations while in pits the rotting is along a hemispherical front in homogeneous rock, but often directed by vertical joints. Their morphology confers very different hydrological regimes: pans fill seasonally for a few weeks to months, while pits are much longer, lasting many months to years. As noted above, because both are on exposed granite, conductivities are low, water is clear and mildly acidic to mildly alkaline, though water in pits is generally a little higher in salts, less clear and of higher pH than in pans. Their faunal composition and ecology are entirely different.

Insects are comparatively more species rich in pits than in pans, with 66% of taxa in pits and only 45% in pans (Pinder *et al.* 2000). However in both, crustaceans are the most common numerically, with pits dominated by *Cypricercus* spp., *Lynceus* spp and *Moina australiensis* and pans dominated by *Boeckella opaqua, Branchinella longirostris, Paralimnadia badia, Ceriodaphnia* spp., *Daphnia jollyi, Macrothrix hardingi,* various chydorids, *Bennelongia* spp., *Cypretta baylyi, Ilyodromus* spp. and *Cypericercus* spp. (Timms 2012a, b). The large array of endemic crustaceans in pans (Pinder *et al.* 2000) is not repeated in pit gnammas with just two species of *Lynceus* (Timms 2013a) and possibly some endemic ostracods (K Martens pers. comm. 2013). The insects in pit gnammas are all widespread eurytopic species, as are almost all in pans, though *Paroster baylyi* and *P. ursulae* are endemic to pans (Hendrich & Fery 2008) as are a few chironomids such as *Allotrissocladius* spp. and *Archaeochlus* spp. (Edward 1989; Pinder *et al.* 2000). Almost all of the insects encountered in pits bred successfully there, as noted by immature stages seen, but fewer are successful in pans. At least in some cases in some years, exemplified by odonatans in 2010 (Timms 2012a), pans dry before the nymphs mature. The insects of pans are largely a subset of those in pits, with notable exceptions listed above, and all dispersing actively as adults. Probably many pit gnammas, especially bigger ones, act as reservoirs for flying species without resistant eggs (see below). The contention by Hendrich & Fery (2008) that their new species of *Paroster* survive pan desiccation by resistant eggs is almost certainly wrong given similar species of *Paroster* disperse into other pans as soon as they fill, breed and eventually leave (Timms 2012a). Crustaceans are advantaged by their resistant eggs so that they are preadapted to seasonally drying pans. Passive egg dispersal is not as efficient as active adult dispersal of insects (Hulsman *et al.* 2007; Vanschoenwinkel *et al.* 2007), so that during long periods of marked climatic changes in southwestern Australia, isolated populations of crustaceans speciated giving the multiple varieties and species in many genera seen in the pans today (Bayly *et al.* 2011, Pinceel *et al.* 2013).

Occasionally some pan species such as *Paralimnadia badia, Caenestheriella mariae,* and *Boeckella opaqua* are found in pit gnammas (Table 1), but this is explicable by flooding from surrounding pans. Sometimes species typical of pans such as *Paraborniella tonnoiri* occur in pits; this can only be attributable to misplaced breeding events and unexceptional given this species is also known elsewhere from non-pan sites (Jones 1974). Finally, the three pit gnammas on Bullamanya Rock with their abundant *Chironomus tepperi,* could be a ready source for this species in the nearby pan gnammas on this rock where this species is unusually abundant (Timms 2012a). The same phenomena could well apply to insects in general when there are pit gnammas near a suite of pan gnammas, so that some of the insects seen in these pans could have a nearby source (Jocqué *et al.* 2007a).

Besides preadaptation to desiccation in the crustaceans, many species in pans also exhibit some physiological and behavioural adaptations to living in this stressful environment. Strong UV rays in the clear waters are counteracted by many with dark cutaneous pigments (e.g. *Paralimnadia badia, Daphnia jollyi, Macrothrix hardingi,* most chydorids) or red colouration internally (e.g. *Boeckella opaqua*). *Branchinella longirostris* tends to avoid the problem by typically staying close to the bottom during strong daylight (B V Timms unpubl. data). By contrast none of the crustaceans in the deeper pit gnammas have protective colouration. Some chironomids, particularly *Paraborniella tonnoiri* are cryptobiotic in pans, thus enabling them to not only survive desiccation, but to emerge as soon after the pond fills and be the first chironomid to reproduce (Jones 1974; Timms 2012a). No ecological or physiological adaptations have been observed in pit species where they would be of no advantage, though it is possible the red *Lynceus* seen in some pits have haemoglobin to enable respiration in possibly reduced oxygen at the bottom of pits with much organic matter.

CONCLUSIONS

The bare granitic rock catchments of pit gnammas result in their waters being of low salinity, and generally clear and slightly alkaline, similar to water in pan gnammas on similar rocks. The greater depth of pits compared with pans means pit gnammas as not as hydrologically restricted as pan gnammas which affects their fauna. First, special adaptations to short hydroperiods and strong UV light are not needed; second, climatic gradients are not so influencial in species composition; third, access for dispersers is more restricted in pit gnammas because of their greater spacing and perhaps covering; fourth, perhaps surprisingly, speciation has been greater in pans than pits probably because their greater numbers on many isolated rock outcrops and specialised habitat provided ideal conditions for speciation in a fluctuating climate. By contrast pit gnammas are unremarkable, (except for their mode of origin) and unspecialised small pools widely spaced across the landscape.

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Appendix 1 Physical and chemical features of core pit gnammas.

	Name	Nearest town	Coordinates	Volume m^3	Times visited	Mean conductivity ±SE (µmS/cm)	Mean turbidity ±SE (NTU)	Cumulative species richness	Mean species richness ±SE
Northwest District									
1	Oak Flat West	Goomalling	31° 08' 21"S; 116° 52' 46"E	1.95	4	146.2 ± 24.9	37.5 ± 30.8	19	8.8 ± 1.4
2	Oak Flat East	Goomalling	31° 08' 20"S; 116° 52' 49"E	1.66	4	114.0 ± 26.5	8.6 ± 4.5	15	8.8 ± 1.2
3	Yellari South	Beacon	30° 19' 44"S; 117° 49' 58"E	6.12	5	76.4 ± 16.2	29.5 ± 10.8	15	11.2 ± 1.1
4	Yellari North	Beacon	30° 19' 44"S; 117° 49' 58"E	0.12	5	139.2 ± 73.0	108.7 ± 86.9	22	8.4 ± 1.0
5	Washington South	Beacon	30° 09' 06"S; 117° 34' 41"E	45.16	4	122.0 ± 48.5	19.7 ± 5.4	25	12.5 ± 2.5
6	Washington Northwest[1]	Beacon	30° 08' 52"S; 117° 34' 46"E	0.17	4	121.7 ± 54.6	10.6 ± 2.3	20	9.2 ± 1.9
7	Washington Northeast[3]	Beacon	30° 08' 57"S; 117° 34' 41"E	0.25	4	156.0 ± 44.9	17.5 ± 10.7	12	4.7 ± 0.8
8	Remlap North[2]	Beacon	30° 02' 04"S; 117° 37' 50"E	7.45	4	82.2 ± 24.3	6.0 ± 0.8	22	9.5 ± 1.2
9	Bullamanya South[2]	Paynes Find	29° 09' 53"S; 117° 39' 36"E	1.36	5	77.6 ± 13.5	3.7 ± 0.5	18	6.0 ± 0.6
10	Bullamanya North[2]	Paynes Find	29° 09' 52"S; 117° 39' 36"E	3.36	5	92.6 ± 23.5	3.7 ± 0.5	22	5.8 ± 0.9
North District									
11	Wondoning Hill	Beacon	30° 34' 36"S; 118° 04' 43"E	1.35	4	65.0 ± 26.0	12.0 ± 6.6	11	6.5 ± 1.2
12	Cadigan North[3]	Bencubbin	30° 46' 53"S; 117° 52' 22"E	0.10	4	110.5 ± 35.6	18.7 ± 7.3	11	5.2 ± 0.5
13	Cadigan Mid[2]	Bencubbin	30° 46' 54"S; 117° 52' 22"E	4.31	4	149.0 ± 29.4	6.3 ± 1.1	14	7.8 ± 0.6
14	Cadigan South[2]	Bencubbin	30° 46' 54"S; 117° 52' 22"E	1.09	4	170.7 ± 31.6	10.4 ± 3.6	18	9.5 ± 0.5
15	Trayning Far Southwest	Trayning	30° 59' 29"S; 117° 50' 46"E	3.23	4	246.0 ± 16.8	29.5 ± 20.2	28	15.0 ± 1.8
16	Trayning Southwest	Trayning	30° 59' 29"S; 117° 50' 46"E	0.61	4	57.5 ± 10.2	17.5 ± 12.5	21	9.2 ± 1.2
17	Trayning Mid[2]	Trayning	30° 59' 29"S; 117° 50' 47"E	0.52	4	241.5 ± 107.6	12.2 ± 7.3	28	13.8 ± 2.8
18	Trayning Northeast[1]	Trayning	30° 59' 28"S; 117° 50' 47"E	1.49	4	155.0 ± 43.1	14.0 ± 6.9	31	13.5 ± 2.9
19	Trayning Far Northeast	Trayning	30° 59' 28"S; 117° 50' 47"E	0.57	4	203.6 ± 37.4	3.7 ± 0.7	15	7.5 ± 0.8
20	Wattoning	Mukinbudin	30° 46' 11"S; 118° 11' 14"E	0.35	4	587.2 ± 138.9	4.4 ± 0.6	14	5.5 ± 0.6
Northeast District									
21	Willogyne North	Mukinbudin	30° 45' 59"S; 118° 16' 27"E	14.24	4	110.5 ± 66.2	30.8 ± 21.4	25	12.5 ± 1.6
22	Willogyne South	Mukinbudin	30° 45' 59"S; 118° 16' 27"E	15.39	4	151.5 ± 77.3	40.0 ± 22.2	27	11.8 ± 1.2
23	Beringbooding North	Mukinbudin	30° 33' 31"S; 118° 29' 42"E	110.00	5	222.6 ± 35.5	20.5 ± 6.1	32	16.2 ± 1.5
24	Beringbooding Southwest	Mukinbudin	30° 33' 38"S; 118° 29' 35"E	23.60	5	156.8 ± 34.0	6.8 ± 0.8	20	11.0 ± 1.7
25	Melancobbing	Mukinbudin	30° 40' 12"S; 118° 32' 21"E	22.62	5	115.2 ± 32.5	8.0 ± 1.6	37	14.4 ± 2.2
26	Yanneymooning	Mukinbudin	30° 43' 04"S; 118° 33' 24"E	0.44	5	70.8 ± 18.4	6.0 ± 0.8	24	9.6 ± 0.9
27	Quanta Cutting	Mukinbudin	30° 51' 49"S; 118° 25' 46"E	11.28	5	92.2 ± 20.0	12.8 ± 3.8	29	13.6 ± 1.4
28	Isoetes[4]	Mukinbudin	30° 54' 11"S; 118° 33' 20"E	0.20	5	125.0 ± 39.1	5.0 ± 0.0	8	3.2 ± 0.5
29	Weira	Mukinbudin	30° 59' 54"S; 118° 23' 13"E	26.84	5	53.0 ± 19.5	49.6 ± 19.5	26	13.4 ± 1.2

South District									
30	Roe[4]	Mt Walker	31° 59' 37"S; 118° 48' 40"E	1.52	4	81.0 ± 32.7	5.0 ± 0	7	3.0 ± 0.4
31	Twine Far North[4]	Mt Walker	32° 06' 26"S; 118° 57' 22"E	0.14	4	96.0 ± 46.0	5.0 ± 0	8	3.5 ± 0.3
32	Twine North	Mt Walker	32° 06' 34"S; 118° 57' 27"E	0.35	5	86.8 ± 14.3	19.3 ± 11.1	13	5.0 ± 0.3
33	Twine Mid	Mt Walker	32° 06' 51"S; 118° 57' 27"E	4.05	5	162.2 ± 28.9	5.3 ± 0.3	18	6.8 ± 0.9
34	Twine Shrub[2]	Mt Walker	32° 06' 53"S; 118° 57' 27"E	0.47	5	475.0 ± 102.6	11.6 ± 2.3	16	5.8 ± 0.7
35	Twine Southeast[2]	Mt Walker	32° 06' 53"S; 118° 57' 28"E	1.35	5	88.4 ± 15.3	19.6 ± 1.3	18	7.4 ± 0.5
36	Humps North	Hyden	32° 18' 41"S; 118° 57' 37"E	0.86	5	67.0 ± 10.9	16.4 ± 2.5	23	7.6 ± 0.9
37	Humps South	Hyden	32° 18' 46"S; 118° 57' 38"E	0.25	5	84.6 ± 1.1	5.0 ± 0	12	5.6 ± 0.5
38	Meeking[3]	Hyden	32° 12' 53"S; 119° 05' 04"E	0.15	4	273.6 ± 57.0	5.0 ± 0	11	3.5 ± 0.6
39	Wheelers[3]	Hyden	32° 19' 59"S; 119° 17' 10"E	0.04	4	39.3 ± 26.1	5.0 ± 0	5	1.8 ± 0.5
40	Baohm	Hyden	32° 21' 34"S; 119° 12' 02"E	0.44	4	69.6 ± 26.2	26.6 ± 23.5	14	7.2 ± 0.9
Southeast District									
41	Forestiana North[1]	Hyden	32° 24' 42"S; 119° 12' 03"E	0.06	4	150.2 ± 42.6	19.2 ± 7.4	14	9.2 ± 1.3
42	Forestiana South[3]	Hyden	32° 24' 42"S; 119° 12' 03"E	0.07	4	129.6 ± 41.9	5.0 ± 0	5	1.5 ± 0.6
43	Cave Rock[4]	Widgiemooltha	31° 39' 40"S; 121° 13' 38"E	0.29	4	69.6 ± 6.0	5.0 ± 0	3	2.5 ± 0.3
44	Higgensville North	Norseman	31° 44' 41"S; 121° 34' 08"E	2.08	4	150.0 ± 31.8	41.2 ± 7.3	16	11.2 ± 0.4
45	Higgensville Mid	Norseman	31° 44' 41"S; 121° 34' 08"E	0.71	4	209.0 ± 46.4	38.0 ± 26.8	17	11.0 ± 0.7
46	Higgensville South	Norseman	31° 44' 41"S; 121° 34' 08"E	0.19	4	105.2 ± 38.9	15.6 ± 6.4	12	7.0 ± 0.3
47	Higgensville Southwest[3]	Norseman	31° 44' 41"S; 121° 34' 07"E	0.24	4	114.0 ± 54.1	6.6 ± 1.4	8	5.0 ± 0.3
48	Buldania East	Norseman	32° 07' 56"S; 120° 55' 38"E	2.48	4	207.0 ± 19.8	91.6 ± 12.7	21	14.0 ± 0.6
49	Buldania South	Norseman	32° 07' 56"S; 120° 55' 38"E	0.43	4	159.4 ± 16.2	11.0 ± 3.3	13	7.8 ± 0.6
50	Buldania West	Norseman	32° 07' 56"S; 120° 55' 37"E	1.99	4	449.4 ± 80.0	30.4 ± 8.4	17	8.2 ± 1.4

[1] floods to greater area and depth
[2] cleaned out November 2010
[3] capped
[4] lotic site

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Role of neuregulin-1β in dexamethasone-enhanced surfactant phospholipid synthesis in rat fetal type II pneumocytes *

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Surfactant production is known to involve a cellular communication between lung fibroblasts and the type II pneumocytes. Glucocorticoids induce the production of a peptide by lung fibroblasts, fibroblast-pneumocyte factor (FPF), which sequentially acts on type II cells to enhance the synthesis of surfactant phospholipid. Our findings show that fibroblast-conditioned medium (FCM), generated in the presence of dexamethasone, not only enhanced surfactant phospholipid synthesis in type II cells but also contained an elevated concentration of neuregulin-1β (NRG1β). Even though it has been earlier proposed that leptin has many of the characteristics of FPF, recent research has revealed that NRG1β also has many similar atributes. In the current study, exposure of the type II cells to a commercially available form of NRG1β (heregulin-1β) directly stimulated by more than three-fold the rate of phospholipid synthesis ($p < 0.05$). Although similar in magnitude, the effect of heregulin-1β appeared to require a longer time of exposure to that reported for leptin. There was no increase in the gene expression of NRG1β when lung fibroblasts were exposed to dexamethasone, irrespective of the concentration of dexamethasone used, or the time of contact of the cells to the steroid. Thus the glucocorticoid-induced increase in the level of NRG1β in FCM was not the result of enhanced expression of the NRG1β gene. The inability of dexamethasone to induce a significant increase in NRG1β gene expression in lung fibroblasts suggests that the elevated concentration of NRG1β might be the result of enhanced cleavage of the membrane-bound neuregulin precursor. In summary, these findings not only support but significantly extend the concept previously promoted that NRG1β plays an essential role in the differentiation and maturation of the lung in the later stages of gestation. Moreover, together these studies suggest that FPF may be a complex mixture of agents capable of motivating surfactant synthesis.

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Paleoenvironmental investigation of Caladenia Cave fossil mammals: consolidating Holocene climate change patterns in southwestern Australia *

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Quaternary paleoenvironmental research on the Swan Coastal Plain of Western Australia has focused primarily around Perth and the extreme southwest, with very little work conducted to the north between 29° and 32° S. Marine invertebrates in the Swan River, calcrete deposits along the coast, previously worked vertebrate cave assemblages and fossil pollen floras pulled from swamps on Rottnest Island and in the extreme southwest provide evidence for an increase in rainfall during the mid to late Holocene, but are chronologically inconsistent. Many of these records used multiple sites and concluded with one chosen site and date as evidence of regional climate change. Other dates such as those for Rottnest Island are highly specific to a single location, an island environment being climatically isolated from the mainland, but assumed to represent greater coastal southwestern Australia. Many of these investigations also use various incompatible dating methods across marine and terrestrial environments where the dates have not yet been calibrated.

Using fossil mammal remains excavated in the 1970s from Caladenia Cave (EM-17) in the East Moore cave area, 100 km north of Perth, this investigation explores the communities of the Caladenia Cave District between 7000 BP and the present. Climate change events were found to be in chronological synchronisation with newly calibrated records to the north and south on the Swan Coastal Plain. A loss of the species characteristic of semiarid and arid regions such as *Phascogale calura*, *Perameles bougainville* and *Lagorchestes hirsutus* indicates an increase in rainfall around 4.7 ka (cal. BP). This increase when mapped spatially with previous records mentioned above show a pattern in the timing of an increase in effective precipitation, in the mid to late Holocene, moving north and inland from the coast according to the orographic effects of the Darling and Gingin Scarps. A change to small sieve-mesh aperture at a late stage of the excavation created a sample-based bias, towards species with larger remains, preventing a statistically significant paleoecological interpretation. This bias has been previously recognised and termed 'differential recovery' due to its selection of certain species based on the size of their remains. Correspondance analysis of the minimum number of individuals from the assemblage showed this bias has had a strong influence on the faunal abundances. The relative abundance data were normalised by sample in an attempt to accommodate the differential recovery of identifiable remains. The output of a principal components analysis then grouped the small mammal species of the Caladenia Cave core assemblage by a primary factor that appears to be substrate related, but no significant interspecies relationships could be determined. This result is similar to previous conclusions from an analysis of Hastings Cave in Jurien Bay to the north on the Swan Coastal Plain. Substrate areas have remained relatively unchanged in the Caladenia Cave District during the Holocene, the dune systems having been deposited during the Pleistocene.

Experiments into a quantifiable measure of the effects of differential recovery will be explored at a later date, as this proved to be of major detriment to this research. The implications of these results may include the suggestion of standardisation of sieve mesh apertures across paleontological and zooarcheological excavations.

Future research on the wider Swan Coastal Plain using similar techniques to match cave surface fossil mammal relative abundances to local substrate areas should elucidate the paleocommunities, eliminating the need for resource-intensive excavations. The presence of now locally extinct small mammals in the upper layers of the Caladenia Cave deposit are indicative of the pre-European fauna on the northern Swan Coastal Plain. The Moore River National Park, located less than 10 km from Caladenia Cave, presents an excellent opportunity for reintroduction of these species and rehabilitation of the original vegetation formations. With most of the land on the northern Swan Coastal Plain cleared for urban development and agricultural purposes, the National Park is a well-located sanctuary for each of the substrate-based communities elucidated from this research. With greater investment of funding and labour into the management of the park, this area would be an excellent conservational resource for the biodiversity hotspot of southwestern Australia.

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Identifying the genetic cause of an internationally unique, naturally occurring muscular dystrophy in Western Australian Merino sheep *

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Muscular dystrophies (MDs) are neuromuscular disorders characterised by chronic, usually progressive, skeletal muscle weakness. Individuals often lose walking ability and can suffer terminal cardiorespiratory complications. Determining the genetics of a disease helps provide diagnosis, prognosis, genetic counselling, and the basis for rational therapeutic design.

A naturally occurring sheep model of congenital progressive MD was identified in Western Australia in the 1950s and preserved as a research colony, cared for initially at Murdoch University and later at the University of Western Australia's Shenton Park facility. During this time, the inheritance was established to follow an autosomal recessive pattern. Further investigations revealed the clinical and histological features of ovine congenital progressive muscular dystrophy (OCPMD).

OCPMD is novel with respect to its pathological features and distribution: this collection of pathologies having never before been observed in a single disease. OCPMD shares features in common with the human diseases nemaline myopathy and myotonic dystrophy, but targeted investigations prior to this project have discounted the genes involved in those pathologies as being causative of the disease.

Animal models of human disease are integral to the investigations of disease pathophysiology, as well as the development and trial of potential therapies. One of the major hurdles in the treatment of MD is delivery to the target tissue, which in humans is distributed through a much larger area relative to current most popular animal models of MD, mice. The similarity between skeletal muscle mass and distribution in humans and sheep mean that an ovine model of MD would be incredibly valuable, representing a significant improvement over those currently being utilised. Another advantage of developing a sheep model is the increased amount of tissue available for biopsy and subsequent pathophysiological investigations relative to smaller mammals. This is a major benefit as the specificity of muscle degeneration in the MDs is still poorly understood and requires further study to elucidate.

Successfully characterising the causative gene(s) in OCPMD would thus enable a possible target for new therapies and may open new lines of investigation into the better understanding and treatment of MD in humans.

The International Sheep Genome Consortium (ISGC) has been working for a number of years to develop a virtual sheep genome to enable the kinds of investigations into sheep genetics that are possible in other, better developed, genomes such as the bovine or human. A contributing member of the consortium, James Kijas (CSIRO), provided several data sources to assist our investigations: an affected and a carrier individual from the OCPMD flock were whole-genome sequenced on the Illumina platform; nine affected and five carrier individuals were SNP genotyped on the '50K SNP Chip' developed by the ISGC (containing 49 034 single nucleotide polymorphisms conserved in sheep); and the latest release of the virtual sheep genome (version 3.1.) was provided for use.

This project utilised a two-pronged approach to investigate the genetics of OCPMD. First, bioinformatics analysis of SNP genotyping for the nine affected and five carrier individuals in concert with the virtual sheep genome was undertaken, enabling homozygosity mapping, genetic linkage and association mapping to be carried out. Additional SNP genotyping was carried out later in the project to increase the statistical power, resulting in 14 affected and six carrier individuals for the final analyses. Second, molecular biological approaches were undertaken to further investigate the identified prime candidate gene by cDNA and gDNA sequencing.

This ambitious, multidisciplinary honours project combining both *in silico* and molecular techniques has identified a prime candidate gene for a causative genetic variant in the OCPMD flock: a ubiquitously expressed gene not previously associated with disease, which has a muscle-specific isoform. It has additionally provided the first evidence in sheep of this isoform, previously only reported in humans, mice and rats. Thus it has laid the groundwork for further investigations into this gene and the OCPMD pathology leading to a possible pinpointing of the causative disease mutation in future work.

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Sustainable use of light for chemical and electrical energy production *

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The Earth receives around 1.9 x 10^6 EJ of energy in visible light each year but only a fraction of this sunlight energy is being converted to biomass (chemical energy) through the process of photosynthesis. There is no doubt our fossil fuel resources are depleting; therefore there is an urgent need for an alternative source of renewable energy that is sustainable. This project works on the potential of developing a novel cultivation system for maximising the use of solar energy by combining solar panels with outdoor microalgae ponds for the production of both chemical and electrical energy.

Out of all photosynthetic organisms, microalgae, due to their fast growth rates, ability to grow on seawater and use of non-arable land, have been identified as a potential source of raw material for chemical energy production. Only a fraction of the electromagnetic spectrum of sunlight in the wavelength range 400–700 nm (also known as the photosynthetic active radiation or PAR) is absorbed by chlorophyll and other accessory pigments of the algae. This spectrum of visible light covers the range from the violet-blue wavelengths over green to orange-red wavelengths.

Although most research work so far has focused on the effects of light quantity or irradiance intensity on the growth, morphology and pigmentation of microalgae, it has also been successfully identified that the colour of light also plays a vital role in vegetative development, reproductive induction and growth rate in microalgae. Therefore part of this research project that we are currently investigating is to identify the light spectrum or colour that is required by the selected microalgae strains for its growth and productivity.

Solar panels have also been used worldwide for electrical energy production but the most efficient commercially available solar cell can only convert ~17% of the solar spectrum into electricity. Certain types of solar panels absorb strongly in the green part of the solar spectrum but not as much as in the blue or the red part. On the other hand, it is interesting to note that some groups of microalgae (i.e Chlorophyta) only require the blue and red part of the light spectrum for its growth and productivity.

This has led to our current work on combining both energy production systems which would allow for a full utilisation of the solar spectrum thus enabling the production of both chemical and electrical energy from one facility making efficient use of available land and solar energy. In this research experiment, we are trying to place a modified solar panel as a filter above the algae culture to modify the spectrum of light received by the algae and utilise the unused parts of the spectrum to generate electricity. In simple terms, we would be giving the microalgae the colour of light required to grow while converting all the unused light spectrum into electricity through the use of photovoltaic devices. Furthermore, another great advantage would be that the harvested algal biomass can be used as a feedstock for production of biodiesel, feed, food and other high-value bioactive products.

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Effect of different light spectra on the growth, productivity and composition of microalgae *

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Microalgae are among the most promising renewable sources for the production of high value products, chemicals, and biofuels. The algae are unique within the Plant Kingdom in the diversity of their light-harvesting pigments in each phylum and in many of their classes. Microalgae are considered for converting light energy to chemical energy through photosynthesis. Light (both quality and quantity) is the main limits to the growth, productivity, composition and distribution of microalgae. However, photosynthesis only uses the parts of the solar spectrum in the range 400–700 nm, which is called photosynthetically active radiation (PAR).

The PAR spectrum is absorbed by various pigments with different efficiency depending on their absorption spectra. In fact the quality and intensity of the light can change simultaneously and the microalgae must adapt to both. The rate of microalgal photosynthesis depends on the rate of captured quanta, which is determined by light absorption properties of microalga cells, and intensity and spectral quality of the light field. Moreover, the efficiency of algal photosynthesis depends on the spectral overlap between solar irradiation and the pigments' absorption spectra. The achievable light to product conversion efficiency and photosynthetic productivity are the most important factor in determining cost in most microalgal production systems. Recent development in the improvement of solar energy conversion to chemical and electrical energy in microalgal production system has been proposed and developed, e.g. the solar spectral converter technology, and the combination of photovoltaic modules with microalgal culture system. In addition, the strain selection and characterisation become an important part in any developments of applied phycology.

Therefore, studies and information regarding the light quality as the main limiting factor of microalgae growth and productivity can promote the improvement of indoor and outdoor semicontinuous culture systems. Illumination of certain parts of PAR spectrum can create an optimum light utilisation for selected potential microalgae. In this research, the effect of three different light spectra—white, blue (407–488 nm) and red (621–700 nm)—on the growth, productivity and biochemical composition (lipid, protein, carbohydrate and chlorophyll content) of four potential microalgae—*Nannochloropsis* sp. strain MUR 266, *Pleurochrysis carterae* strain CCMP 647, *Cymbella* sp. strain MUR 258, *Botryococcus braunii* strain CCAP 807/2 (race B)—with different pigment profile grown in batch and semicontinuous modes were investigated. It is important to note that the amount of energy for each light spectrum was the same (2.23±0.10 $W.m^{-2}$), and the algae have been grown and adapted to certain light conditions for at least 20 days.

The microalgae *Nannochloropsis* sp. MUR 266 (Eustigmatophyceae; Chlorophyll *a*), *Pleurochrysis carterae* CCMP 647 (Prymnesiophyceae; Chlorophyll *a* & *c*), *Cymbella* sp. MUR 258 (Bacillariophyceae; Chlorophyll *a* & *c*) and *Botryococcus braunii* CCAP 807/2 (Trebouxiophyceae; Chlorophyll *a* & *b*) were cultured in aerated 500 mL Erlenmeyer flasks. The culture of *Nannochloropsis* sp. was grown in f/2 medium at 3.3% NaCl salinity, *P. carterae* in modified f/2 medium at 3.3% salinity, *Cymbella* sp. in f medium at 10% salinity and *B. braunii* in freshwater CHU-13 medium with a light:dark photoperiod of 12 h:12 h at 27±3°C. The initial cell density was 5×10^4 cells.mL^{-1}. Illumination was from the bottom of the culture system and the specific light spectrum was achieved by filters so that the cultures received an equal irradiance of 2.23±0.10 $W.m^{-2}$ at the specific photosynthetically active radiation (PAR) wavelength and full-width half-maximum (FWHM) of unfiltered white (400–700 nm), blue (FWHM 407–488 nm) and red (FWHM 621–700 nm). The specific growth rates (μ), biochemical and chlorophyll composition, and productivities were determined using the Algae R&D Centre, Murdoch University standard methods. The repeated measures one-way analysis of variance (ANOVA) was performed using SPSS for Windows (ver. 21.0, IBM SPSS).

In summary, cells grown semicontinuously under blue light presented the highest growth rate (μ) for *Nannochloropsis* sp. (0.21) and *Cymbela* sp. (0.14), whereas for *P. carterae* the highest was obtained under white light (0.18). and for *B. braunii* under red (0.07). All species also responded differently to the light spectra with respect to their biomass, proximate composition (as a percentage of ash-free dry weight), and chlorophyll composition and productivity ($g.L^{-1}.d^{-1}$). Blue light enhances algal growth and metabolism of lipid and protein synthesis relatively to white or red, while the exposure of red light in contrast results an increase of carbohydrate content. A chromatic spectrum of blue and red light can be used to enhance the growth, biochemical production, and chlorophyll composition, due to the characteristics of the photosynthetic process. The exposure of a monochromatic light with a specific wavelength (blue and red) can lead to the accumulation and manipulation of microalgae growth, biomass and biochemical productivity both for enhancement and inhibition. The responses of microalgae are different and can be species-dependent based on their pigment profiles, absorption spectra and chromatic adaptive mechanisms.

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European carcass classification system does not predict eating quality *

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Global beef consumption is declining, and this is also reflected in the European markets. Variable eating quality is seen as a major factor in the decline in beef consumption and delivering a product of consistent and reliable quality is vital for the industry to maintain its profitability and market share. The European beef grading systems of EUROP Conformation score and Fat cover are used to determine the value of beef carcasses in Europe. EUROP Conformation score is determined by eye muscle area, carcass weight and a visual conformation assesment, and as such increasing EUROP Conformation score correlates with increasing lean meat yield. Previous work has highlighted that with increasing lean meat yield, there is a concurrent decrease of intramuscular fat. Decreasing intramuscular fat has a strong, negative, impact on trained taste panel scores for tenderness, juiciness and flavour. Therefore we hypothesise that increasing EUROP score will correlate with decreasing eating quality.

Seven cuts (striploin, outside, rump, tenderloin, oyster blade, knuckle and topside) from 100 French and Polish cattle were grilled to a medium doneness of 60°C. In total 1200 untrained French and Polish consumers rated the steaks between 0 and 100 for tenderness, flavour, juiciness and overall liking, according to Meat Standard Australia protocols. These scores were then combined on a weighted basis (0.3, 0.3, 0.1, 0.3 respectively) to make a fifth term called the Meat Quality score (MQ4). At slaughter, following standard European grading practices, all cattle were graded using EUROP conformation scores ranging from the most muscular, 'E' to the least muscular 'P'. Each of the 5 classes, 'E,' 'U,' 'R,' 'O' and 'P' were further subdivided into high, middle and low, giving a total of 15 EUROP conformation scores. The results were analysed using a mixed linear model with the MQ4 score as the dependant variable, cut, age and EUROP score fitted as fixed effects, and animal identification and the person responsible for conferring the EUROP grade fitted as random terms.

There was an effect of EUROP conformation score on MQ4, but only within oysterblade, rump and knuckle. However in general the differences between these scores followed no clear linear trend across the EUROP conformation score categories. These results were not affected by correcting the model for carcass weight or USA Ossification score. Similiary when EUROP Fat cover was added to the model there was still no clear relationship between EUROP conformation score and MQ4.

Contrary to our hypothesis EUROP Conformation has no consistant, linear, relationship with the eating quality of beef. The absence of a clear linear trend across EUROP conformation scores limits the ability for production recommendations to be made to industry. Thus, while the EUROP system may adequately describe carcass muscling characteristics, it does not predict eating quality. The industry should consider using a system more related to eating quality to determine the monetary value of carcasses destined to be consumed as fresh beef, rewarding those producers supplying the meat most preferred by consumers.

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Comparison of carbon stores by two morphologically different seagrasses *

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INTRODUCTION

The recent emphasis on global change has intensified research in the carbon sequestration potential of seagrass ecosystems (Nellemann *et al.* 2009). Most estimates on seagrass carbon storage are, however, derived from studies of a few species and habitats. Lavery *et al.* (2013) showed an 18-fold difference in carbon stores among Australian seagrasses highlighting the importance of inter-habitat variability in carbon stocks. One implication from this is that the factor of seagrass species may play a key role in the variation in carbon stores beneath those studied meadows. Different seagrass species have inherently dissimilar traits, well summarised by the seagrass functional-form model in Carruthers *et al.* (2007). This functional-form model differentiates seagrasses based on morphological plasticity, rhizome persistence and occurrences in varying depositional environments, among other traits. A further extension of this model is suggested such that the seagrass species may shift from low to high transitions of standing crop biomass between extreme ends of the model. Of interest, the two seagrass genera *Halophila* and *Posidonia* are placed at opposite ends of the functional-form model. *Halophila* has a small biomass with less persistent rhizomes while *Posidonia* has the opposite traits.We hypothesise that meadows of smaller, ephemeral seagrasses with low standing crop will have less accumulated carbon compared to the larger and more persisting forms with higher productivity and biomass. Estuarine seagrass habitats dominated by *Halophila ovalis* and *Posidonia australis* were studied to compare the total carbon stocks and origin of the preserved carbon.

METHODS

Four seagrass meadows were studied: *P. australis* from Oyster Harbour (OH: 34°58'58.3"S, 117°58'29.9"E) and Waychinicup Inlet Estuary (WI: 34°53'35.9"S, 118°19'57.7"E), and *H. ovalis* from Swan River Estuary (SR: 32°00'46.1"S, 115°47'43.5"E) and Harvey Estuary (HE: 32°38'00.3"S, 115°38'51.7"E). To allow viable comparisons not confounded by habitat types potentially influencing the depositional environment of allochthonous carbon, this study compared estuarine meadows of both species. Both tidal and swell exchanges dominate WI while OH, SR and HE are wave dominated. Three sediment cores were each collected from the four sites in 2012 by either manually hammering core barrels or by vibracoring (Vibecore-D, SDI) into the sediments. These cores were sliced, dried and weighed for dry bulk-density analysis. Alternate slices of ground and acidified (1 M HCl) subsamples were encapsulated and analysed for total organic carbon (OC) and stable carbon isotope composition values ($\delta^{13}C$) at the UC Davis Stable Isotope Facility (continuous flow isotope ratio mass spectrometer analyser, Sercon). For testing differences in sedimentary OC content among different seagrass species and sites, a two-way nested ANOVA (SPSS 19) was applied (species as fixed factor, site nested within species) and post-hoc (Tukey) tests were further applied to assess differences among sites within the same species.

RESULTS

The sampling resulted in different lengths for all cores. After corrections for sediment compression during coring (Glew *et al.* 2001), core lengths ranged from 170 cm to 250 cm. To allow comparisons, OC characteristics in all sediment cores were standardised for the top 170 cm-thick deposits. In the *Posidonia* cores, localised agglutination of plant detrital matter was observed. This coarse *Posidonia* detritus was more abundant in OH cores. The top 10 cm of *Halophila* cores contained low amounts of coarse plant detrital matter becoming less evident until the 25 cm depth and was absent below this level. Mean OC content was higher in *P. australis* sites (mean±SE; 2.03±0.19% at OH and 1.12±0.08% at WI) compared to *H. ovalis* sites (0.34±0.15% at HE and 0.16±0.03% at SR). The mean OC content in 170 cm-thick deposits was 6-fold higher in *P. australis* sites (1.58±0.21%) compared to *H. ovalis* sites (0.25±0.07%; $p<0.05$). The OC content was significantly higher in *P. australis* OH cores compared to those in WI ($p<0.01$), while the OC content among *H. ovalis* sites was similar ($p>0.05$). $\delta^{13}C$ values of sedimentary organic matter in *Posidonia* meadows at OH were more positive (-9.89‰ to -14.0‰) than in WI (-13.0‰ to -19.5‰). The $\delta^{13}C$ signatures in both *Halophila* sites followed similar trends in all cores (ranging from -16.0‰ to -21.5‰).

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* Extended abstract of a paper presented at the Royal Society of Western Australia Postgraduate Symposium 2013 held at Murdoch University on 12 October 2013.

DISCUSSION

Comparison of carbon stocks between species

The OC stocks in 170 cm-thick deposits beneath *P. australis* meadows were 6-fold higher than in *H. ovalis* sites. The difference in OC accumulation between the two different seagrass species can be partially explained by the higher biomass and productivity of *P. australis* meadows (1300–2100 g DW m^{-2} and 0.23 g DW m^{-2} d^{-1}, respectively) compared to the *H. ovalis* meadows (76 g DW m^{-2} and 0.01 g DW m^{-2} d^{-1}: Duarte & Chiscano 1999). In addition, *Posidonia* species invests larger amounts of carbon into below-ground organs (1220 g DW m^{-2}) compared to small seagrasses such as *Halophila* (21 g DW m^{-2}), which invests more energy in rapid clonal propagation resulting in high turnover rates. The below-ground organs of seagrasses are more recalcitrant than above-ground organs, and therefore are more likely to end buried *in situ* as detrital matter, particularly for *P. australis* rhizomes which can grow 20–50 cm beneath the sediment surface. Only in the event of major scouring would these below-ground tissues be uprooted and exported. Furthermore, the dense and relatively high canopy of *P. australis* stabilises the sediment, enhancing sediment deposition and reducing re-suspension, and increasing the likelihood of OC stocks being preserved. This contrasts with *H. ovalis* meadows with a sparse and low canopy. Below-ground living organs are ephemeral growing at 5–10 cm below the sediment surface. Any detrital matter produced by *H. ovalis* is thus more likely to be scoured and allochthonously transported rather than remain buried *in situ*.

Source of carbon

The δ^{13}C values of sedimentary organic matter in *P. australis* sites (mean = -13.82‰ for both sites) are indicative of a strong influence of *P. australis*-derived input. The reported δ^{13}C values of *P. australis* organs range from -9.9‰ to -11.9‰ (Hemminga & Mateo 1996), consistent with those observed in the deposits. In contrast, δ^{13}C values at *H. ovalis* sites (mean = -19.16‰) are indicative of low amounts of seagrass detritus contributing to the sedimentary organic pool. The reported δ^{13}C values of *H. ovalis* organs range from -6.4‰ to -15.5‰ (Hemminga & Mateo 1996), much more enriched than those we observed in the sediments. The δ^{13}C values of allochthonous sources of organic matter (i.e. seston, algae and terrestrial organic matter) are more negative than seagrass isotopic signatures, in the range of -13‰ to -29% (Smit *et al.* 2005; Loneragan *et al.* 1997) and may account for the relatively depleted values in the *H. ovalis* sediments. Previous studies have commented on the ability of the *Halophila* canopy to effectively trap allochthonous carbon (Fonseca 1989) and our findings are consistent with an earlier study which found that *H. ovalis* had the second highest OC accumulation after *P. australis* meadows, possibly due to the nature of the depositional environment and canopy-trapping of allochthonous carbon (Lavery *et al.* 2013).

Within-species variation

Both *H. ovalis* sites showed similar vertical profiles in the mass and δ^{13}C values of buried OC. In contrast, while we expected the two *P. australis* sites to show similar vertical OC content trends and δ^{13}C values through the cores, OH meadows contained double OC stocks of mainly seagrass-derived OC compared to WI. Subsequent radiocarbon dating of the cores from WI (unpubl. data; accelerator mass spectrometry, Australian Nuclear Science and Technology Organisation) showed that at similar stratigraphic levels, the organic matter age varied by ~1000 calibrated years before present. A plausible explanation for this variation in the chronostratigraphy among cores is a scouring event leading to major sediment reworking at WI resulting in a loss of buried OC through erosion. Sediment scouring may also occur in estuaries with higher degree of tidal and swell influence, or during extreme events, and thus could affect the sedimentary OC and δ^{13}C characteristics.

CONCLUSIONS

The comparison of OC stocks and δ^{13}C signatures of sedimentary organic matter in the two morphologically different seagrass species demonstrated significant variations in both the carbon accumulation potential as well as the origin of buried carbon among the seagrasses. Meadows of the larger *P. australis* accrue 6-fold more OC than those of the smaller *H. ovalis* species. Seagrass-derived organic matter forms the bulk of those higher stores while allochthonous organic matter is the major contributor in the *Halophila* sites. However, within sites of the same species, further variations in carbon characteristics may be exhibited due to natural ecological processes. The results of this study clearly confirm that both species and habitat may contribute to variation in the OC stored in seagrass meadows and that more comprehensive scrutiny of the factors accounting for those variations are required to improve global estimates of Blue Carbon storage in seagrass meadows.

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A game of cat-and-mouse: do habitat structure and fire history influence native rodent foraging behaviour *

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Invasive predators have caused significant species declines and extinctions worldwide, especially in insular systems like Australia. Foxes and feral cats are responsible for the extinction of at least 22 Australian mammal species in the past 200 years. To avoid being killed by predators, prey species modify their spatial or temporal use of habitat, or the time when they undertake different activities. Giving-up-density (GUD) experiments are commonly used to test the influence of predation risk on prey species. In a controlled setting, a decrease in the GUD corresponds to a decrease in predation risk, and vice versa. The aim of this experiment was to investigate the foraging strategies of two native rodents in respect to microhabitat structure and vegetation fire history. We predicted that rodents would spend more time foraging in bush microhabitats and in unburnt habitat, and that the positive effect of bush microhabitats would be less in unburnt areas.

We studied the foraging behaviour of Mitchell's hopping mouse (*Notomys mitchellii*) and the sandy inland mouse (*Pseudomys hermannburgensis*) at Charles Darwin Reserve in the northern Wheatbelt of Western Australia. Artificial foraging patches and the GUD technique were used to measure foraging activity. We established 144 feeding trays across six burnt and six unburnt sites; half the trays were placed in 'open' microhabitat and the other half under vegetation cover ('bush'). Feeding activity was monitored for six to eight nights in February and April 2013.

The data pooled across both months indicated that both species prefer to forage in bush microhabitat, rather than in the open. Terrestrial carnivores, the dingo and feral cat, occur in the study area, as do other predators like the barn owl, albeit less commonly. Feral cats were the most common predator during the study period and are a known predator of both *P. hermannsburgensis* and *N. mitchellii*. The higher GUDs recorded in open microhabitat indicate that animals spend less time foraging in the open, which may reflect risk-aversive behaviour in the presence of predators.

The data indicated that both species prefer to forage in burnt habitat rather than unburnt. Both species spent less time foraging in unburnt habitat, which suggests that the perceived risk of predation was greater in unburnt areas. Given that feral cats prefer to hunt in open areas, we expected that native rodents would prefer to forage in the denser unburnt areas, where cats should hunt less often. However, the data did not support this. Bush microhabitats benefit rodent foraging activity; so reduced habitat structure close to the ground in unburnt habitat may be responsible for higher GUDs in these areas. Habitat measurements should reveal whether this is the case.

The positive effect of microhabitat was weaker in unburnt areas. We expected that microhabitat structure would be less important in unburnt habitat because the taller vegetation would mediate predation risk. However, this may not be the case since overall rodents foraged less in unburnt habitat. Microhabitat may have been less important in unburnt areas if vegetation was less dense close to the ground.

The findings of this study will have applied outcomes for nature conservation. Future experiments will test the effect of native and introduced predator cues on foraging behaviour. Preservation or enhancement of habitat structure may reduce the impact of introduced predators on native fauna. Land management actions like prescribed burning should be informed by ecological knowledge if native species are to be conserved.

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Foetal kidney vascular development of the mammal *Sus scorfa* *

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All vertebrates have a kidney and throughout the evolution of vertebrates the function of the kidneys has consistently been for the removal of nitrogenous waste and the maintenance of osmotic balance within the animal. However, mammals have specialised the kidney to allow for the concentration of urine above that of blood thus allowing for increased conservation of water. The functioning of the kidney relies on the correct structure of the nephron within the kidney. The basic vertebrate nephron contains a glomerulus encompassed by the Bowmen's capsule, which passes the ultrafiltrate from the blood into the nephron, and the proximal tubule that reabsorbs molecules like glucose and other chemicals to be conserved by the body whilst actively secreting larger molecules such as penicillin. Finally the filtrate passes into the collecting duct which directs the final product for transport out of the ureter. As noted the mammalian kidney is able to concentrate urine through the re-absorption of water which occurs in the loop of Henle. The presence of a loop of Henle in a kidney indicates the capacity for a kidney to concentrate urine if needed.

Apart from the presence of the loop of Henle there is another difference in mammalian kidney structure/ function and that is in the development of the kidney. Unlike other vertebrates, in mammals the developing kidney does not necessarily have to be fully functional during gestation due to the functioning of the placenta. Like other organs within the mammal (lungs and liver) it is possible then to delay development of the kidneys until close to birthing when they will need to be fully functional. The development of the vascularisation of the kidney and by association the kidney itself is something that has been discussed in a number of publications but has yet to be characterised visually. The aim of this study was to examine the kidneys of foetal pigs at different stages to characterise the rate and development of the glomeruli within the kidney and thus the rate and development of the nephrons and the overall structure of the kidney.

Foetal pigs were collected from the local abattoir and frozen before use. These pigs were separated into two age groups based on gestational size and included 68 days into gestation (9–10 weeks) and 114 days into gestation (16–17 weeks). A mid-ventral incision was made to gain access to the dorsal aorta just anterior to the kidneys. Gastric and mesenteric arteries were clamped off and a cannula inserted and tied into the dorsal aorta. 10% saline solution containing 1000 I.U. Heparin per millilitre was flushed through the renal arteries via the cannula until the colouration of the kidneys change to pale indicating the removal of the blood. Mercox solution was mixed as per instructions and was injected into the renal arteries via the dorsal aorta until a colour change was noted based on the colour of the Mercox. The animal was then left to sit for an hour until the Mercox had hardened into a resin cast. For a period of a week the animal was placed in a bath of sodium hydroxide to allow all excess tissue to be digested leaving a cast of the kidney vascular system. The casts were cleaned in increasing concentrations of ethanol for storage before imaging took place. Macroscopic images were obtained using Olympus S2-CTV dissection microscope before smaller samples were extracted from the casts. Samples were dried using a Polaron critical point drier before being gold coated for electron microscopy. Images were taken using a Philips XL30 Scanning Electron Microscope at 5–10kv acceleration with a spot size of 3.

From the macroscopic images that were collected it was clear that there was a difference between the overall macro-anatomy of the late-stage kidney compared to the early-stage kidney. Unlike the late-stage kidney, with its clear cortex medulla differentiation, no such differentiation was shown in the early-stage kidneys. In some cases the glomeruli ruptured under the pressure of either the saline solution or the Mercox and a cast of the entire Bowmen's capsule and nephron was inadvertently taken. From these extra casts it was shown that, although the nephrons are present in the early-stage kidneys the loops of Henle have yet to be developed. Upon closer examination of the glomeruli within the casts there are two noticeable differences between the late-stage and early-stage kidneys. First, there was a large difference in the average size of the glomeruli: the glomeruli in early-stage kidneys were found to be up to four times larger than the glomeruli found in late-stage kidneys. Second, the overall distribution of glomeruli also appears to have changed: once the cortex/medulla differentiation was taken into account it was also seen that the number of glomeruli based on density has also increased in the late-stage kidneys.

Without a clear cortex/medulla differentiation in the early-stage kidney it is clear that the early-stage kidney does not have the capacity to concentrate urine as a typical adult mammalian kidney would. A cast of a nephron in the early-stage kidney was also captured and showed no loop of Henle which further indicates no capacity to concentrate urine. The cast of the early-stage nephron however does indicate the possibility of a functional kidney even at this early stage of development. The functioning of the available glomeruli relies primarily on the overall surface area of the glomeruli as a whole and as such it was unexpected to have such a dramatic decrease in the size of individual glomeruli. A decrease in size may increase overall pressure and filtration capacity of the glomeruli and an increase in complexity and glomeruli density ultimately increases surface area of the glomeruli in the entire kidney. The overall structure of the late-stage kidney was as expected when compared to the known structure of the adult mammalian kidney. This structure was expected as the late-stage foetal pigs were near birth and would need a fully functional kidney for survival. Within the earlier stage kidneys however we have seen what is essentially a structurally sound (and possibly functioning kidney) but one that is significantly different to that of an adult mammal. Comparisons with the structure of adult non-mammalian (reptilian) kidneys, however, show a structure that is similar in many aspects to the early-stage kidney of the foetal pig which may be a case of ontogeny recapitulating phylogeny.

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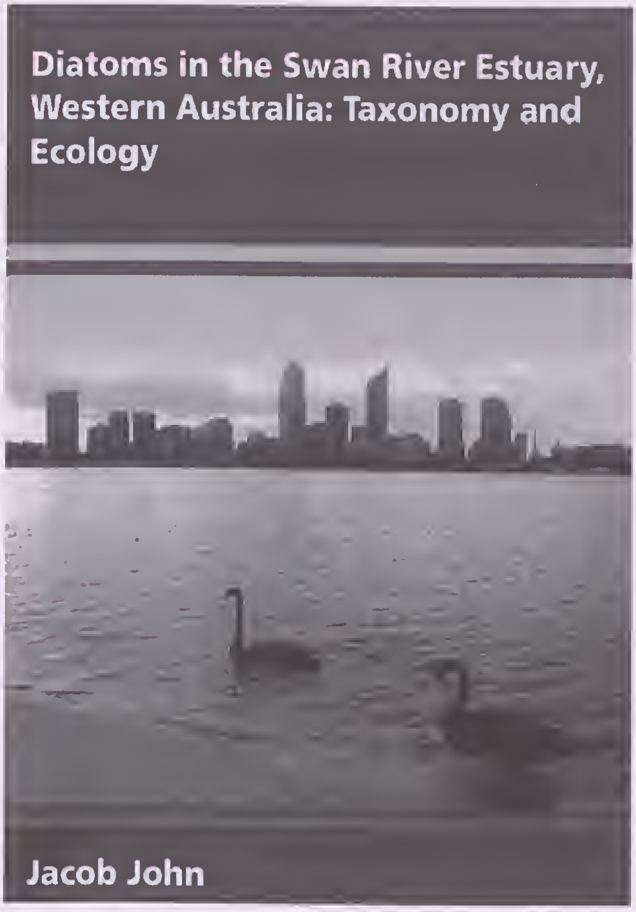
Book Review

Diatoms in the Swan River Estuary, Western Australia: Taxonomy and Ecology

Diatoms in the Swan River Estuary, Western Australia: Taxonomy and Ecology by Jacob John

Koeltz Scientific Books, Konigstein, Germany 2012, 456 pages, 139 plates; hard cover. ISBN 978-3-87429-429-4


Diatoms in the Swan River Estuary, Western Australia: Taxonomy and Ecology
Jacob John

This book represents a revised edition of *The Diatom Flora of the Swan River Estuary Western Australia*, part of the *Bibliotheca Phycologia* series, first published in 1983 by the author. The original title was widely used around the world by students, academics and those working in regulatory and private organisations, proving a valuable taxonomic reference on estuarine diatoms. In subsequent years the book became out of print, after which obtaining a copy was extremely difficult. This revised volume entitled *Diatoms in the Swan River Estuary, Western Australia: Taxonomy and Ecology*, contains updated information, figures and taxonomic notes, and is a welcome edition for diatom enthusiasts. The book is well presented, with over 456 pages in hardcopy format, quality binding and large font size. It is easily navigated, comprising Introduction, Materials and Methods, followed by five brief chapters on the Swan River, and a taxonomic section, which provides the bulk of the text and figures. There are some typographical errors and formatting inconsistencies scattered throughout, the most obvious of which is the repetition of four paragraphs on page 5, although these may be easily rectified by the author in an updated edition. The index of diatom taxa at the rear of the book is considered useful for those referring to the book primarily as a taxonomic resource.

The diatom descriptions that make up the majority of the book are based on studies from the Swan River by the author, which began in the late 1970s and continued intermittently to 2012. These studies represent an increased sampling effort from the original edition, which was limited to work carried out in the early 1980s. The front two sections of the book contain the Introduction, with background on the Swan River, and the Material and Methods for the studies. Descriptions of sample sites (and an associated map) are included, detailing the 10 frequently sampled stations located along the Swan and Canning Rivers in the upper and lower reaches of the system. Collection techniques and diatom processing, analysis and identification procedures are also provided in the methods, noting the additional collection of samples that form part of the revised edition of the book. There is a summary of the physico-chemical data collected during the 1980s, with water quality data presented as an Appendix. A brief synopsis of the diatom data and reference material is placed at the end of the Materials and Methods, outlining the taxa most frequently encountered, and common bloom-forming species observed in the Swan River.

Following these sections, Chapters 1 to 5 are new additions to the revised volume. Chapters 1 to 3 examine the ecology of the Swan River Estuary, based on various studies conducted in the 1980s and 1990s, supported by ample tables and figures. They focus on seasonal succession patterns of phytoplankton, in particular planktonic diatoms, with the distribution pattern of epiphytic diatoms also investigated. Controlling factors influencing algal assemblages in the Swan are the hydrological regime, which in turn affects salinity and nutrient concentrations, considered the driving factors for shifts in species distribution. In Chapters 4 and 5, changes to the Swan over the last 30 years are examined, and the challenges that lie ahead to maintain the health of the river are outlined. These two chapters focus on hydrology, ecology, land use and the problems associated with urbanisation and industrialisation along the edges of the Swan. Historical impacts have led to land degradation, salinisation, sedimentation and excessive nutrient input, causing nuisance blooms of dinoflagellates and cyanobacteria. To combat these problems, regulatory bodies (including the Swan River Trust) and community groups have taken interactive approach to developing and implementing management strategies for the river. The author briefly concludes with potential restoration and monitoring measures for the Swan in Chapter 5, ending on a positive note, on the roles diatoms may play in assessing the river's health going forward. Chapters 1 to 5 are considered valuable to broaden the reader's knowledge on the river and algal distribution patterns. However there is a sense that at times, the material presented interrupts the general flow of the revised edition, and therefore may have been better served as a separate, published volume.

The taxonomy of diatoms from the Swan River Estuary begins on page 52 and provides the results to the studies outlined in the introduction and methods. As a result, this part of the book may have been better placed directly following these sections. The author states the classification system adhered to and the format that ensues, in order to use the taxonomic descriptions as intended. Taxa are presented in alphabetical order by genera, accompanied by morphological descriptions, and information on distribution and habitat. Since the first edition of the book was published, there have been substantial revisions in diatom taxonomy, with the author attempting to accommodate much of the recent changes. This is reflected in the number of genera described, consisting of 114 genera and 365 taxa, in comparison to the first volume, which described 74 genera and 358 diatom taxa. While the taxonomic nomenclature has been updated, the majority of the descriptions remain the same, complete with several new additions, proving testament to the quality of the original descriptions. Along with the taxonomic notes, more than 100 diatom figures (plates) are presented, in many cases comprising more than one image per taxon. While many of these were included in the first edition of the book, several high quality scanning electron microscopy (SEM) images have been added, and these highlight the complex morphology of diatoms. With much of the book focused on diatom taxonomy and nomenclature, an introduction to diatom morphology would have been valuable, although notes highlighting key morphological features are associated with many of the SEM images.

Overall, *Diatoms in the Swan River Estuary, Western Australia: Taxonomy and Ecology* makes a substantial contribution to diatom research in Western Australia. The book will no doubt have widespread appeal for those with an interest in estuarine ecology, aquatic ecology and water management. It is highly recommended for individuals affiliated with universities, regulatory authorities and environmental consultancies, where algology and diatom taxonomy are at the forefront. This volume will make an attractive and welcome addition to any diatom reference library in Australia and around the globe.

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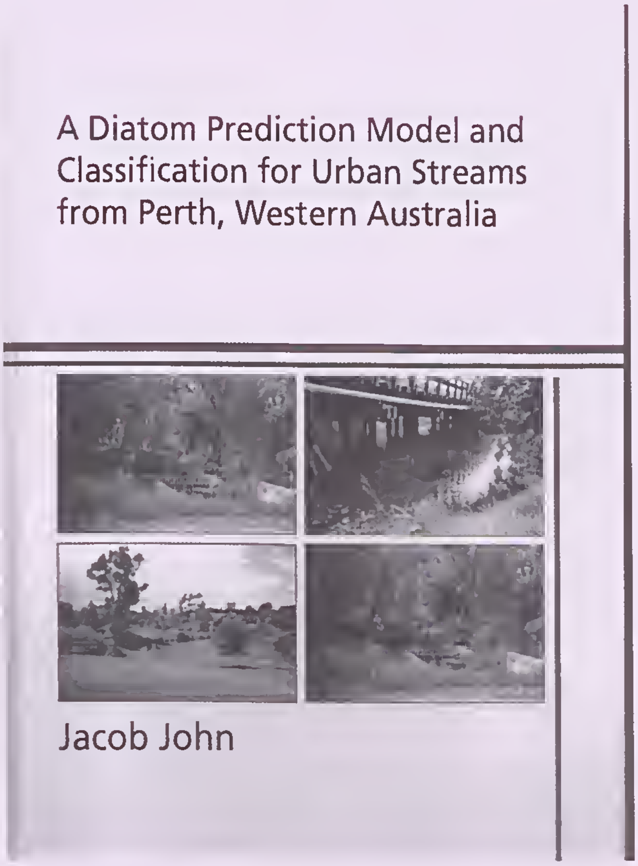
Book Review

A Diatom Prediction Model and Classification for Urban Streams from Perth, Western Australia.

A Diatom Prediction Model and Classification for Urban Streams from Perth, Western Australia by Jacob John

Koeltz Scientific Books, Germany, 2012: 166 pages, hard cover; ISBN 978-3-87429-430-0



A Diatom Prediction Model and Classification for Urban Streams from Perth, Western Australia

Jacob John

Diatoms are well known to be sensitive indicators of environmental conditions. This informative volume investigates the relationship between these unicellular algae and the health of urban streams and drains in Perth, Western Australia. It represents a synthesis of the author's earlier volumes *Diatom Prediction and Classification System for Urban Streams* and *A Guide to Diatoms as Indicators of Urban Stream Health*.

The tone of the volume is set in the opening pages with a dedication to Professor Ruth Patrick, a pioneer of river health assessment using diatoms. The material that follows is divided into five main chapters, appended diatom iconographs and selected site descriptions.

The introductory chapter commences with a case study of an unexpected cyanobacterial bloom in the Swan River estuary. This effectively outlines the influence of urban streams and drains and their associated nutrients on the water quality of Perth's major rivers, providing context for the work presented. The case study is followed by a well-rounded literature review addressing various facets of water quality, management and monitoring. Particular attention is paid to the impact of urbanisation in the Perth region, with examples of nutrient loads and drainage systems. A strong case for the use of diatoms as bioindicators is also made. The first chapter ends with the objectives of the project, a primary theme being the use of diatoms to classify and assess the health of urban streams and drains in Perth.

Chapter 2 provides an overview of the study area, outlining the relationship between the Swan River estuary, associated catchments and tributaries, primary among these being the Canning River, Helena River and Ellen Brook. A main focus however, is the growing issue of eutrophication in the estuary and the factors driving this process. The author elaborates on the various sources of nutrients, in particular urban streams and drains, some of which are known to make a substantial contribution to nutrient loading in the Swan River estuary. The final section of Chapter 2 outlines the selection of sampling sites; 200 sites chosen to represent the urban catchment area around the Swan–Canning estuary system. Insight is given into the classification of these streams and drains into reference (relatively pristine) and monitoring (impacted), based on parameters such as water quality, surrounding land-use and peripheral vegetation.

Chapter 3 provides further detail on site locations before presenting field and laboratory methods. This leads into a comprehensive section on data analysis, providing a good background for the results to follow. The spreadsheet and example calculations referred to in relation to the diatom index (Appendix 3/3a) are not included in the volume, but are available on request from the author.

A large sample size has enabled the compilation of robust sets of environmental and biotic data (including fresh periphyton and diatom counts) from the urban streams and drains of Perth. The author has used these data to great effect, employing a suite of statistical analyses to explore the relationship between the distribution of diatom communities and stream/drain conditions (Chapter 4).

Of particular note is a two-way table which allows the reader to examine the patterns in the diatom data from both a species and site perspective. From this, groups of sites dominated by indicator species for either reference or monitoring (impacted) conditions can be identified. Another feature is the diatom index, a tool developed to help classify and assess the health of urban streams and drains using diatom assemblages. The data treatments have also resulted in the reclassification of almost 160 sites and the identification of various diatom indicator species, each with potential applications for monitoring and management of urban streams and drains in Perth.

The final chapter (Chapter 5) brings together the findings of the study, outlining the major achievements. The concluding remarks are well presented in succinct summary points, incorporating recommendations for future work. The diatom iconographs that follow are a very useful addition, helping to build knowledge of diatom taxonomy in the region.

The volume is nicely presented in a durable hardcover format, with the inner material printed in black and white. While the black and white presentation tends not to detract from the overall message, some of the figures would have benefitted from the use of colour and increased resolution on printing. Presentation within the volume could also have been improved by the correction of some formatting and typographical issues, in particular labelling errors and the placement of figure headings in Chapter 4. Amendment would be recommended for any future updates of the volume.

Overall, the volume provides substantial information on the diatoms of Perth's urban streams and drains. It also highlights the usefulness of this algal group for bioassessment. In addition, the information and techniques presented could potentially be adapted to assess urban stream health in other regions. The volume represents a valuable resource, recommended for local government officers, environmental consultants, students and those involved in the management of rivers and urban streams.

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